



Pathomechanics of lumbrical and flexor digitorum profundus muscle tears in climbers: A cadaveric model

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ABSTRACT

Lumbrical muscles originate on the flexor digitorum profundus (FDP) tendons and, during fist making, they move in the same direction when FDP muscle produces maximal proximal tendon gliding. Injuries of the bipennate lumbricals have been described when a shear force acts between the origins on adjacent tendons of the FDP, as they glide in opposite directions in asymmetric hand postures. Other structures of the deep flexors complex can be affected during this injury mechanism, due to the so-called quadruga effect, which can commonly occur during sport climbing practise. Biomechanical studies are needed to better understand the pathomechanism. A cadaveric study was designed to analyse the effects of load during the fourth lumbrical muscle injury mechanism. The amount of FDP tendon gliding and metacarpophalangeal (MCP) joint flexion of the 5th finger were calculated. Ten fresh-frozen cadaveric specimens (ten non-paired forearms and hands) were used. The specimens were placed on a custom-made loading apparatus. The FDP of the 5th finger was loaded, inducing isolated flexion of the 5th finger, until rupture. The rupture occurred in all specimens, under a load of 11 kg (SD 4.94), at 9.23 mm of proximal tendon gliding (SD 3.55) and at 21.4° (SD 28.91) of MCP joint flexion. Lumbrical muscle detachment from the 4th FDP was observed, from distal to proximal, and changes in FDP tendons at the distal forearm level too. The quadruga effect can lead to injury of the bipennate lumbrical muscles and the deep flexors complex in the hand and forearm.

1. Introduction

The lumbricals are singular muscles: both their origin and insertion are mobile. They originate from the tendons of the flexor digitorum profundus (FDP) and insert into the extensor apparatus or dorsal aponeurosis of the fingers (Wang et al., 2014). Normally, the third and fourth lumbricals have a bipennate architecture, with their origin in two adjacent FDP tendons, although a high variability among individuals has been described: the 1st and 2nd lumbrical can also be bipenniform, have some origin in the flexor digitorum superficialis, or have a more proximal origin within the carpal tunnel, for example (Belbl et al., 2023).

Their name comes from “Lumbricus”, which means earthworm, because of their thin and elongated architecture. Due to their very small

cross-sectional area (Jacobson et al., 1992) and the high quantity of neuromuscular spindles (Winckler and Foroglou, 1965), they have limited motor function, unlike the interosseous muscles, and instead lumbricals play a crucial role in hand proprioception (Schreuders and Stam, 1996; Leijnse and Kalker, 1995; Wang et al., 2014). During active movement, the lumbricals move in the same direction as the tendons of the FDP when all the fingers of the hand close symmetrically. If their fiber and muscle length were shorter, the extensive tendon gliding of the FDP tendons would cause excessive stretching of the lumbrical sarcomere, hindering its contraction and the generation of muscular strength (Jacobson et al., 1992). In the active movement of the hand into a full fist, the FDP tendons record maximum proximal tendon gliding, averaging 32 mm, according to studies conducted in vivo by Whebé and

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Hunter (1985).

However, what happens when the active flexion is not performed symmetrically by all fingers? Climbers use a highly specialized repertoire of hand gestures during their sports practice. In the so-called one-finger-pockets, two-finger-pockets or three-finger-pockets, some of the fingers exert force against the wall and remain in extension, while the rest of the fingers remain free and tend to flex to the maximum (Schweizer, 2001). This is known as the FDP quadriga effect and occurs due to the multiple connections within the deep flexors complex, causing the different fingers of the hand to be mechanically interdependent during movement (Leijnse, 1997; Schreuders and Stam, 1996; Verdan, 1960). It is in these asymmetrical positions when a lumbrical muscle injury can suddenly and traumatically occur (Lutter et al., 2018; Schweizer, 2003).

Happening in the third and fourth lumbricals, the injury occurs when the bipennate muscle origins dissociate in opposite directions beyond their tolerance range. The shear occurs when one of the adjacent FDP tendons remains fixed in extension, while the other glides proximally (Fig. 1). In its diagnosis, a positive lumbrical stress test induces the injury mechanism and provokes hand palm pain (Schweizer, 2003). It is a low-prevalent and poorly studied injury, which is gaining importance due to the global increase in climbing practitioners following its inclusion in the 2020 Olympics (Lutter et al., 2020). Moreover, it can be

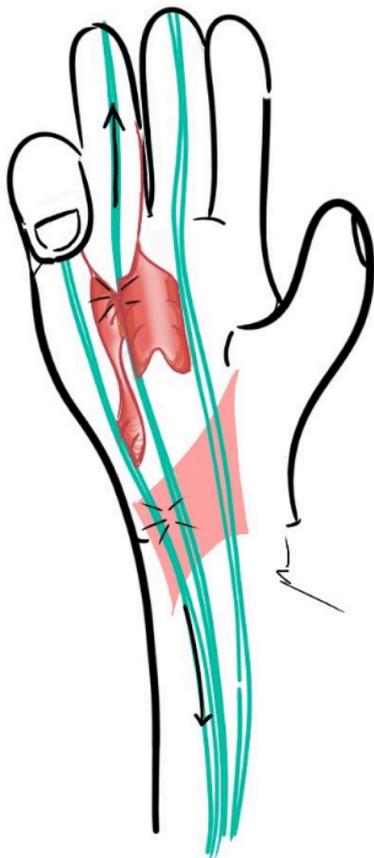


Fig. 1. Schema of the fourth lumbrical muscle injury mechanism in the deep flexors complex. In the schema: FDP tendons of the 3rd, 4th and 5th fingers (green lines); third and fourth lumbricals (red muscle bellies); synovial sheath (wrist portion of the ulnar bursa) and connective tissue surrounding all the flexor tendons at the wrist and distal part of the forearm (red rectangle). Critical points of injury are shown: the distal part of the origin of the fourth lumbrical muscle in the 4th FDP tendon at the palm of the hand, as well as the inter-tendinous connections of connective tissue and the ulnar bursa at the wrist and distal part of the forearm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

easily underdiagnosed in the general population, not just climbers, as these injuries can also occur during manual domestic and work-related activities (Lutter et al., 2018; Wang et al., 2016).

Within the deep flexors complex or the so-called FDP-Flexor pollicis longus (FPL)-Lumbrical complex (Leijnse, 1997), structures additional to the bipennate lumbricals also establish tendon interconnections. These are the common muscular belly of the FDP, and the cross-linking of tendon fibers between tendons, such as the Linburg-Comstock variation. Also, the areolar connective tissue that surrounds the tendons between the distal third of the forearm and the carpal tunnel, and the common synovial sheath called the ulnar bursa (Brand and Hollister, 1999; Leijnse, 1995; Leijnse, 1997; Linburg and Comstock, 1979; Schreuders, 2012; Morro Martí et al., 2015; Yamine and Erić, 2018). This complex creates an indivisible unit, not only in the anatomical study, but also in the clinical exploration of hand function. It determines the interdependence of finger movement and can cause dysfunction. Some syndromes were described, similar to lumbrical injury, especially in the study of the musician's hand (Leijnse, 1992) (Fig. 2).

Could all these interconnection structures of the FDP-FPL-Lumbrical complex become injured, apart from the bipennate lumbricals, during the quadriga effect? Should we actually consider them as lumbrical and FDP muscle injuries? Some studies suggested that findings of FDP tenosynovitis in the ultrasound or MRI were signs of lumbrical tear (Schweizer, 2003; Lutter et al., 2018; Wang et al., 2016). Moreover, often patients suffering from these injuries report pain not only at the palm of the hand, but also at the wrist or forearm.

Lumbrical muscle tears are a lesser-known injury with an increasing prevalence. They often remain underdiagnosed and tend to relapse and symptom chronicity. Further studies that delve into its complex pathomechanics are needed to better understand how the injury occurs, which structures are affected or could lead to symptoms, and also to contribute with new knowledge to improve clinical management.

2. Methods

A cadaveric study was designed to analyse the effects of load during the fourth lumbrical muscle injury mechanism. The amount of FDP tendon gliding and metacarpophalangeal (MCP) joint flexion of the 5th finger were calculated.

The study was approved by the Commission on Ethics in Animal and Human Experimentation of the institution.

Ten fresh-frozen cadaveric specimens (ten non-paired forearms and hands) were used in this study. FDP of the 3rd, 4th and 5th fingers were exposed and dissected separately at the forearm. The tendons of the flexor digitorum superficialis of the 4th and 5th fingers were removed for better visibility.

The specimens were placed on a custom-made loading apparatus. A 2.5 mm Steinmann pin was used on the 2nd phalanx of the 3rd finger to secure the specimen on the apparatus, while the FDP tendon remained free on one side of the pin, as tendon gliding was allowed.

To perform the measurement of tendon gliding, two reference points were marked on the tendons of the 4th and 5th fingers, respectively, using silk sutures. The two suture points were aligned at a 7 cm location from the wrist, in the middle third of the forearm. A ruler was placed on the table to serve as a scale for posterior measurements.

At the forearm, metal staples were used to anchor two dynamometers to the proximal end of the respective FDP tendons: "dynamometer 1" fixed together the 3rd and 4th FDP tendons, and "dynamometer 2" was anchored to the 5th FDP tendon (Fig. 3).

To conduct the experiment, the 2nd, 3rd and 4th fingers were maintained in extension. A load of 1.5 kg was applied on the first dynamometer to secure the 3rd and 4th FDP tendons. Using the second dynamometer, the FDP tendon of the 5th finger was loaded progressively, inducing isolated flexion of the 5th finger. The load was applied kilogram by kilogram, with a resting period of 10 s each time. The experiment ended when rupture occurred. (Fig. 4).

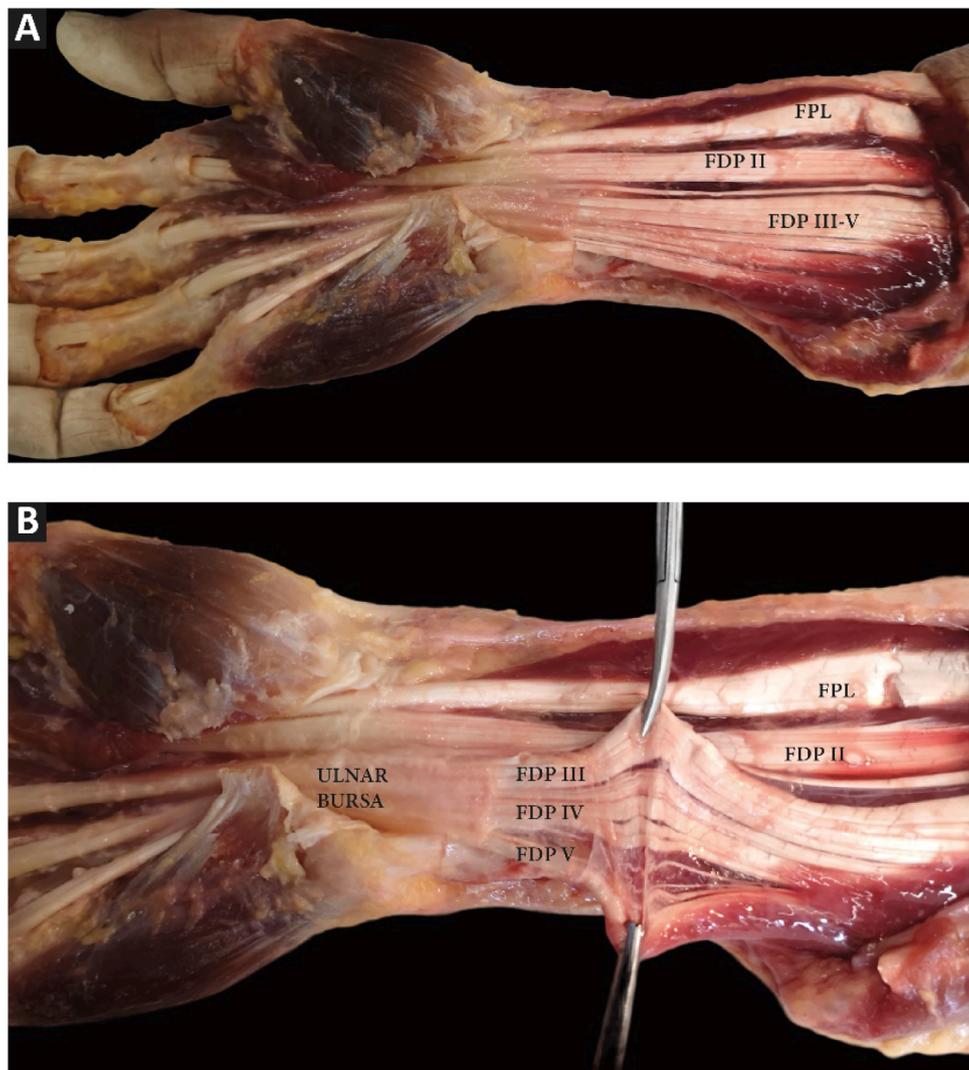


Fig. 2. Images of anatomical dissection of the deep flexors complex or FDP-FPL-Lumbrical complex in one specimen. **2A.** Different anatomical structures establish intertendinous connections. From the left to the right: the bipennate lumbricals at the palm of the hand, the connective tissue and the ulnar bursa at the carpal tunnel and wrist, the cross-linking fibers and intertendinous connections at the distal part of the forearm, and the FDP common muscle belly for the 3rd to 5th fingers. **2B.** On the left side, a detailed view reveals the ulnar bursa. It is the synovial sheath that surrounds all the flexor tendons (FDP and FDS), extending from the distal third of the forearm to form the digital synovial sheath for the 5th finger. On the right side, between surgical forceps, the indivisible ensemble comprising the different tendons of the FDP for the 3rd, 4th, and 5th fingers is shown.

In order to make data collection and measurements easy, video recording (frontal and sagittal views) was employed throughout the experimental process and measurements were subsequently taken in digital format using ImageJ. [See supplemental files \(Video 1\).](#)

The differential FDP tendon gliding was evaluated, measuring the millimetres (mm) of distance between the 4th FDP tendon and the 5th FDP tendon at the forearm, when rupture occurred. The degrees of MCP joint flexion of the 5th finger were also measured by goniometry.

To explore the collected data statistical analyses were performed using IBM® SPSS® Statistics version 25.0.0.1 statistical software. The mean, standard error of the mean, standard deviation (SD), 95 % confidence interval and the kurtosis of the different measurements were predicted.

3. Results

The sample collected a total of 10 specimens (5 males and 5 females) with a mean age of 87 years (SD 9.27), ranging between 70 and 100 years.

The fourth lumbrical rupture in the deep flexors complex occurred in

all 10 specimens, under a load of 11 kg (SD 4.94, standard error of the mean 1.56, IC 95 % 7.46–14.5, asymmetry 0.05, kurtosis 0.53). A distinctly audible crack was heard at the point of injury, accompanied by a sudden flexion of the MCP joint. [See supplemental files \(Video 1\).](#)

Prior to rupture, a mean of 9.23 mm of proximal tendon gliding (SD 3.55, standard error of the mean 1.12, IC 95 % 6.68–11.8, asymmetry -0.56 , kurtosis -0.46) of the 5th finger FDP relative to the 4th finger FDP had occurred. At that point, the flexion of the 5th finger MCP joint averaged at 21.4° (SD 28.9, standard error of the mean 9.14, IC 95 % 0.72–42.1, asymmetry 2.27, kurtosis 5.55).

After the rupture and still under tension of the final number of kilograms, a separation of 37.68 mm (SD 21.1, standard error of the mean 6.68, IC 95 % 22.6–52.8, asymmetry 1.94, kurtosis 4.16) was ultimately produced between the FDP tendons. At that point, the flexion of the 5th finger MCP joint was finally 90.9° (SD 19.7, standard error of the mean 6.24, IC 95 % 76.8–105, asymmetry 0.03, kurtosis 2.13) (Fig. 5).

During subsequent macrodissection, changes were observed not only in the lumbrical muscle at the palm of the hand, but also in the FDP tendons at the wrist and distal part of the forearm. [See supplemental files \(Video 2\).](#)

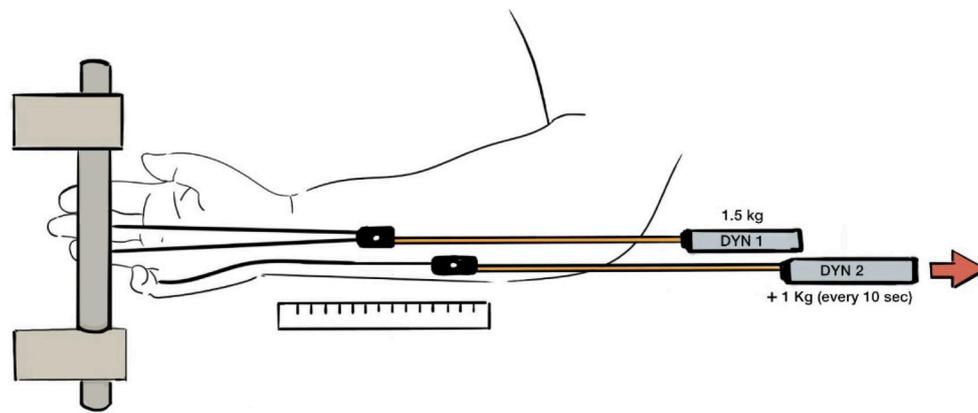


Fig. 3. Methods. Schema of the experimental procedure. One specimen is placed on the loading apparatus, secured by a Steinmann pin on the 3rd finger. 2nd, 3rd and 4th fingers are secured in extension lying under a cylindrical piece of wood, while leaving the 5th finger free to move. “Dynamometer 1” is anchored to the distal muscle end of the 3rd and 4th FDP, and a load of 1.5 kg secures together these two tendons during all the procedure. “Dynamometer 2” is anchored to the distal muscle end of the 5th FDP tendon. The procedure consists of progressively increasing the load to “Dynamometer 2”, 1 kg every 10 s of waiting, until the rupture occurs.

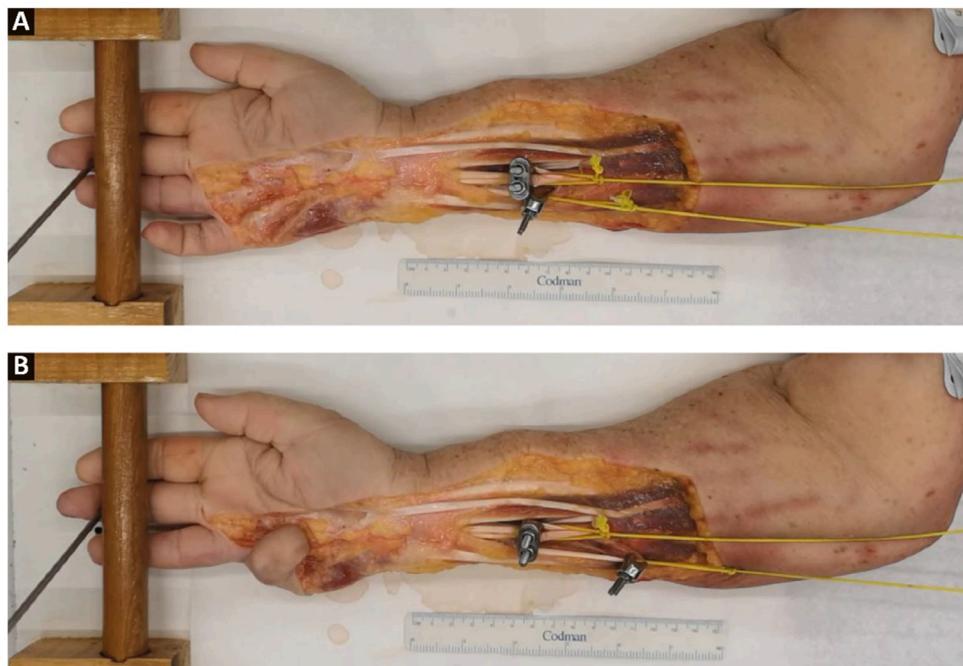


Fig. 4. Methods. **4A.** Before the experimental process, one of the specimens placed on the loading apparatus, which had been previously prepared by dissection and anchored to dynamometers 1 and 2. **4B.** One of the specimens at the end of the procedure. The experiment was interrupted when rupture occurred. Under load, maximal proximal tendon gliding and flexion of the MCP joint of the 5th finger were observed.

Firstly, clear signs of fiber rupture were evident in the fourth lumbrical muscle, which could also show partial or complete detachment from its origin on the 4th finger FDP tendon (Fig. 6A and 6B). Typically, its ulnar origin on the 5th finger FDP remained intact or showed slight signs of detachment in the macrodissection. On the other hand, changes were also noted in the connective tissue and the ulnar bursa surrounding the tendons of the FDP at the distal third of the forearm, at the wrist and carpal tunnel. Discontinuity and loss of mass were observed at this level, and the dissection of the different FDP tendons separately became easier (Fig. 6C and 6D). Moreover, during the experiment, prior to rupture, faint tissue crackling sounds were also audible, possibly corresponding to these small synovial or connective tissue ruptures.

4. Discussion

4.1. Study of the injury mechanism

Since Schweizer (2003) first described lumbrical muscle tears in his series, other studies also examined its incidence, clinical management or evolution, but no studies have delved into the study of the injury mechanism until the present. Our study confirms Schweizer’s hypothesis: the quadriga effect of the deep flexors complex can lead to the injury of the bipennate lumbricals when significant shearing forces act on the muscular belly in a dissociative mechanism between the two FDP tendons.

The study successfully replicated the injury mechanism of the fourth lumbrical muscle in all specimens. In the moment of rupture, there was

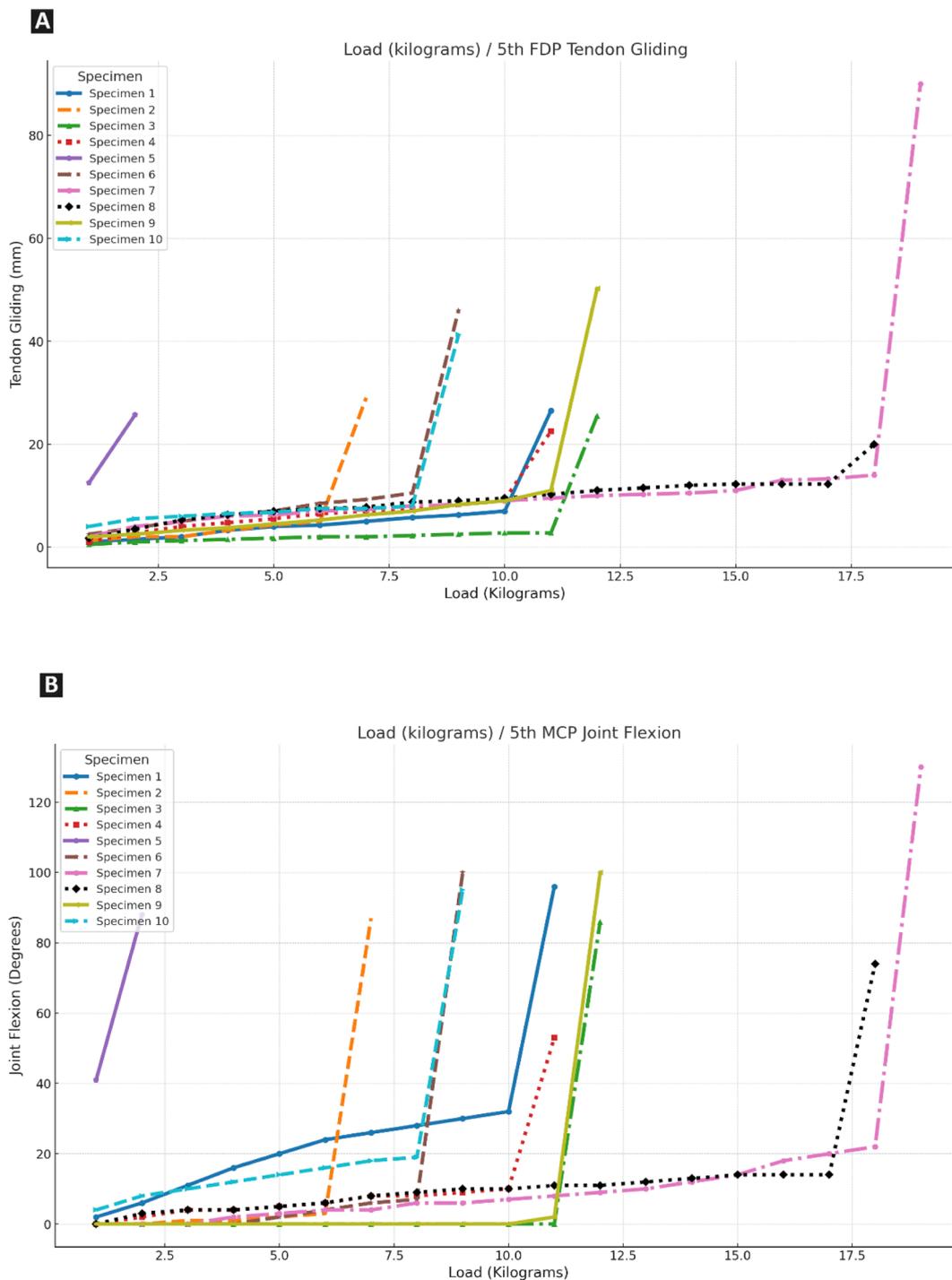


Fig. 5. Charts depicting the study results for all the specimens (created with the Matplotlib data visualization library). **5A.** Equation between the applied load (expressed in kilograms, kg), and the proximal tendon gliding of the 5th FDP versus the 4th FDP (expressed in millimetres, mm). **5B.** Equation between the applied load (kg), and the flexion of the 5th MCP joint (expressed in degrees, °).

an audible crack –corresponding with real patients’ accounts (Lutter et al., 2018; Schweizer, 2003)-, followed by the proximal gliding of the FDP tendon of the 5th finger and a sudden increase in flexion of the MCP joint. This injury is becoming more prevalent among climbing practitioners. It occurs when they adopt asymmetric hand positions (the so-called one, two or three-finger-pockets) and the load increases out of control, either accidentally or due to fatigue. Although it’s commonly a climbing-related injury, some cases have been described related to domestic or occupational activities (Lutter et al., 2018; Wang et al., 2016).

The findings in the posterior dissection confirmed the injury of the

fourth lumbrical muscle, both in its muscular belly and its origin at the FDP tendon. The detachments from the origin on the FDP tendon of the 4th finger were the most prevalent finding, specifically in the distal portion (Fig. 6B).

Although specific studies are needed to confirm the hypothesis, according to the results of this study, the critical point in the lumbrical muscle injury involves detachment starting from the most distal portion of its tendinous origin at the FDP of the 4th finger (which is the finger held in extension at the moment of the injury) towards proximal (Fig. 1). These findings align with the imaging findings described in the

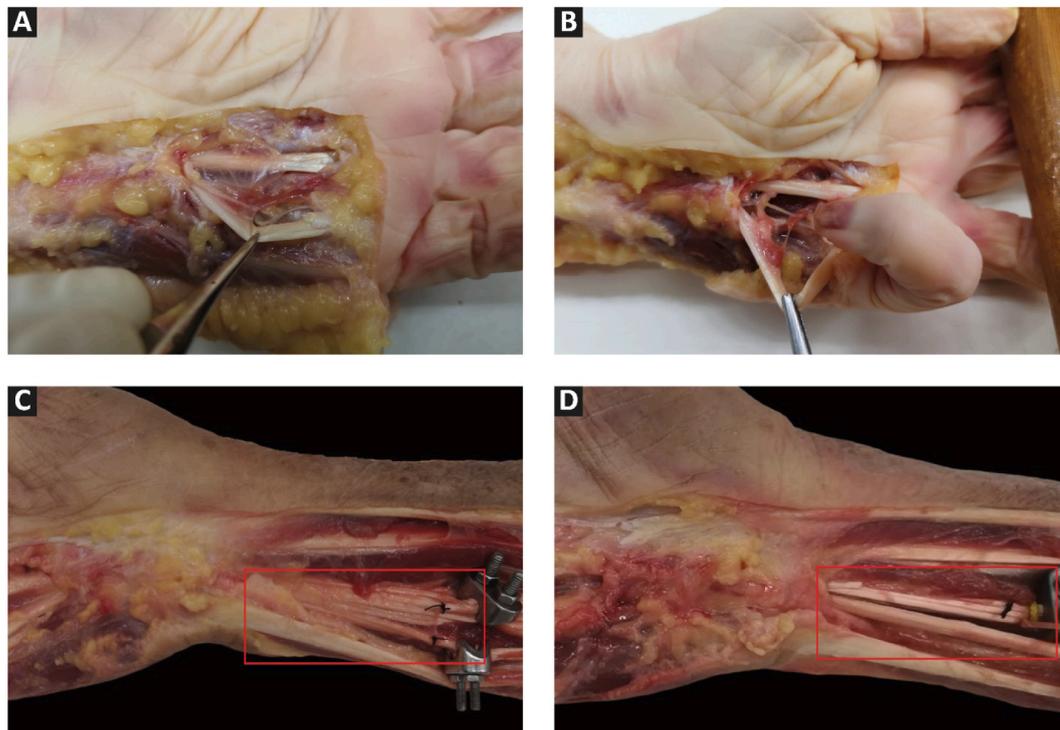


Fig. 6. Key findings during the posterior macrodissection. **6A.** The bipennate fourth lumbrical muscle has two origins on the 4th and 5th FDP tendons. They were visible before the experiment was conducted. **6B.** After the rupture, loss of mass in its muscle belly and partial or complete detachment from the 4th FDP tendon could be observed. **6C.** Connective tissue and the ulnar bursa surrounding the FDP tendons at the distal forearm and wrist level could be observed before the experiment was conducted (rectangle). **6D.** After the rupture, loss of mass at the wrist level and distal forearm was observed (rectangle). The different tendons of the FDP were distinguished easier during the posterior macrodissection; gliding between tendons was also smoother and offered less resistance, at the end of the procedure.

literature: in milder cases, tenosynovitis of the FDP can be observed (Lutter et al., 2018; Schweizer, 2003; Wang et al., 2016), while in more severe cases, detachment from the origin can be observed (Lutter et al., 2018). In any case, these would not be suggestive of indirect signs of lumbrical injury, but rather the actual injury in the FDP-FPL-Lumbricals complex or the deep flexors complex.

4.2. The FDP-FPL-Lumbricals complex injury

FDP tendons produce 32 mm of proximal tendon gliding during fist-making when all the fingers move together (Wehbé and Hunter, 1985). In our study, only 9.23 mm (SD 3.55) of in vitro isolated proximal tendon gliding of the 5th finger FDP was possible while the FDP of the 3rd and 4th fingers remained in extension. Compared to Wehbé and Hunter's results, only a quarter of the total tendon gliding was possible during isolated tendon gliding of the 5th finger. Beyond the 9.23 mm mark, a disruption occurred in the intertendinous connections, resulting in a final maximum differential tendon gliding.

Several authors studied the extensive network of connections in the deep flexors complex. Defining the FDP-FPL-lumbricals complex, Leijnse et al. (1997) described the connections that exist between the tendons of the FDP and FPL, which make the system an indivisible whole and are responsible for the interdependence of finger movements. According to the results of our study, during the quadriga effect in the climbers' hand, the lumbrical muscle is not the only structure that can be injured. There is evidence that other connective tissue and synovial structures within the complex are also affected. The previous crackling sounds during the experiment and the subsequent findings during the dissection of the FDP tendons could prove it. These findings included the loss of substance at the areolar connective tissue and at the synovial sheath of the ulnar bursa, both at the wrist and at the distal part of the forearm (Fig. 6D). The dissection and the visual differentiation of the FDP tendons became

easier compared to the pre-experiment dissection, and a major isolated tendon gliding was possible, with less resistance and more independence between the different FDP tendons.

The present proposal would represent a paradigm shift in the understanding of lumbrical muscle tears. Moreover, this condition should be considered as an injury in the FDP-FPL-Lumbricals complex (Fig. 1). In the diagnosis, the lumbricals would only be one of the possible injury locations, and could cause hand palm pain during the stress test. However, other structures within the complex that could also be affected need to be considered. They could lead to symptoms in other areas such as the wrist or forearm which can also be provoked during the stress test: the connective tissue and the ulnar bursa surrounding all the flexor tendons could lead to symptoms at the anterior-ulnar side of the wrist; and the intertendinous connections and the common muscle belly of the FDP, at the forearm. Other dissociative syndromes in the deep flexors complex had been described in the literature before. Leijnse et al., (1992,1997) had studied certain syndromes in relation to the various connections of the FDP-FPL-lumbrical complex, with a special emphasis on hand gestures in musicians and their relationship with dystonias. The Linburg-Comstock variation, present in 21 % of the population (Yammine and Erić, 2018), had been described as the presence of a connection between the tendon of the FDP of the 2nd finger and the FPL (Linburg and Comstock, 1979), which could cause pain on the anterior-radial side of the wrist in some patients, especially in relation to repetitive manual tasks, and it could coexist with other conditions such as tenosynovitis and carpal tunnel syndrome (Yammine and Erić, 2018).

Therefore, in the management of these injuries, the principles of muscle repair had to be considered, as suggested by Schweizer (2003) and Lutter et al. (2018). But additionally, clinicians had also to take into consideration connective tissue and synovial sheaths histology, the latter characterized by their high irritability and reactivity, which could be the key factor in perpetuating and chronicizing symptoms in some

cases.

It's important to note that this study was conducted in vitro using inert tissues and specimens from older individuals. This should be considered a limitation and taken into account for a better interpretation of the results. Thus, the results can only be extrapolatable with caution to the injury mechanism in living human beings, where muscular and connective tissue structures are healthy, offer greater resistance, and have real-time reactive and contractile capacity. Clinical studies that validate the results are needed in the future.

5. Conclusion

During the quadriga effect in the FDP muscle, different intertendinous connections can be injured when the tendons glide in opposite directions, causing shear. This mechanism can lead to injury in the bipennate lumbricals in the hand, and the FDP muscle in the wrist and forearm, as well as other structures of connective tissue and synovial sheaths in the FDP-FPL-Lumbricals complex can also get involved.

This study aims to emphasize the importance of the whole deep flexors complex within the spectrum of structures involved in this injury mechanism, representing a novel contribution to the understanding of the anatomy and biomechanics of the finger flexors system and to the management of these injuries on clinical practice. Future studies are needed to validate these in vitro laboratory findings against potential imaging findings in real cases.

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Institutional review board or ethics committee

Institutional review board approval was obtained prior to the study. The donation of bodies to the Faculty of Medicine at the Universitat Autònoma de Barcelona (UAB), for teaching, research, and continuous education, is regulated by a document of express acceptance by the donor, which was approved by the Commission on Ethics in Animal and Human Experimentation (CEEAH) of the UAB, procedure number 2904.

Patient involvement statement

The specimens were part of a body donation program in compliance with current ethics and research national legislation. Written informed consent for participation was not required for this study in accordance with the legislation and the institutional requirements.

Data sharing statement

All data relevant to the study are included in the article or are available as supplementary files. Further inquiries can be directed to the corresponding author.

CRediT authorship contribution statement

Núria Carnicero: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Àngel Ferreres Claramunt:** Writing – review & editing, Validation, Resources, Methodology, Data curation, Conceptualization. **Montserrat del Valle Jou:** Writing – review & editing, Validation, Resources, Methodology, Data curation, Conceptualization. **Aroa Casado:** Writing – review & editing, Software, Formal analysis, Data curation. **Alfonso Rodríguez-Baeza:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2024.112196>.

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