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Finger Injury Related to Climbing: Anatomy, Function, Mechanism of Injury, Diagnosis, Treatment

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Abstract

Introduction

Rock climbing has surged in popularity over the past few decades, attracting a diverse range of participants from recreational enthusiasts to professional athletes. While climbing offers numerous physical and mental benefits, it also presents significant injury risks. Rock climbing is a sport that imposes extreme stress on the fingers, particularly on the flexor pulley system. Injuries to these structures can severely impact a climber's ability to perform and progress in the sport. Understanding the anatomy, injury mechanisms, and treatment modalities is essential for effective management and prevention.

Aim of the study

The purpose of this narrative review is to comprehensively describe information on the anatomy, function, mechanism of injury, diagnosis, and treatment modalities of the finger flexor pulley system (FFPS).

Materials and methods

The methodology for the literature search involved using the keyword "pulley" and adding terms such as "treatment", "mechanism", "function", "anatomy", "diagnosis", and "symptoms". The search terms were entered into the PubMed and Google Scholar databases. The review works and clinical trials were taken into account.

Conclusion

Finger flexor pulley system (FFPS) strain is a common overuse injury in climbers, often caused by the crimp grip used in rock climbing. Pulleys A2 and A4 are particularly vulnerable. Diagnosis involves physical examination and imaging tests, such as ultrasonography and, if necessary, magnetic resonance imaging. Grade I to III injuries are typically treated conservatively, while surgical treatment may be necessary for grade IVb injuries. Using a splint or H-taping the fingers after an injury can help prevent further damage and provide support for the affected pulleys.

Keywords: Finger Flexor Pulley System (FFPS), climbing injury, A2 pulley, H-taping, crimp grip

INTRODUCTION

Climbing can be broadly categorized into several types, each with unique risk factors: bouldering: Climbing short but challenging routes without ropes, typically over crash pads [1]. Sport Climbing: is a form of rock climbing that emphasizes the physical challenge of scaling steep and often overhanging rock faces. It relies on permanent anchors fixed into the rock, such as bolts, to protect climbers from falls. Traditional (Trad) climbing placing removable protection gear while ascending [2,3]. Alpine climbing: climbing in mountainous environments, often involving rock, ice, and mixed terrains [4]. Indoor climbing: climbing on artificial walls, often in gyms. Each type of climbing presents different challenges and injury risks. For example, bouldering often results in falls from lower heights, leading to injuries like sprains and fractures, while trad climbing might result in more severe injuries due to longer falls and gear failure

[5,6,7]. Understanding the types of injuries, their mechanisms, and management is crucial for both climbers and healthcare providers. Most injuries include pulley tears, tenosynovitis, and joint problems.[8] Rock climbing, a challenging and exhilarating pursuit, places extraordinary strain on the fingers, particularly impacting the intricate flexor pulley system. This system, composed of a web of tendons and ligaments within the fingers, is crucial for maintaining a secure grip and stability while navigating the vertical terrain. Injuries to this essential system, whether they be pulley sprains or ruptures, can profoundly hinder a climber's ability to ascend and develop in the sport. It is imperative for climbers to prioritize proper training, conditioning, and rest to safeguard against such injuries and sustain optimal finger health in the demanding realm of rock climbing. The flexor pulley system consists of a series of fibrous bands that keep the flexor tendons close to the bones of the fingers, preventing bowstringing during flexion. The main pulleys prone to injury are the A2 and A4 pulleys, which are located at the base of the proximal and middle phalanges, respectively. Pulley injuries occur primarily due to the high forces generated during specific climbing grips, particularly the crimp grip. Explosive moves and falls can also contribute to pulley injuries [2,9,10].

AIM OF THE STUDY

The primary objective of this narrative review is to provide a comprehensive overview of the anatomy, functionality, injury mechanisms, diagnosis, and treatment modalities associated with the finger flexor pulley system (FFPS). With the escalating popularity of the sport of climbing, it becomes imperative to disseminate information and heighten awareness regarding potential injuries, while also striving to achieve a comprehensive understanding of their pathomechanisms to facilitate prevention.

MATERIALS AND METHODOLOGY

The literature search methodology used a comprehensive approach by utilizing the keyword "pulley" in conjunction with related terms such as "treatment", "mechanism", "function", "anatomy", "diagnosis", and "symptoms." These specific search terms were meticulously entered into both the PubMed and Google Scholar databases to ensure a thorough search process. Additionally, the review encompassed relevant clinical trials to provide a comprehensive overview of the topic. The research questions formulated are outlined below:

1. What is the anatomical structure of the finger flexor pulley system (FFPS)?
2. What is the functional significance of FFPS?
3. What is the etiology of FFPS injury?
4. What are the indicative symptoms of an FFPS injury?
5. What is the optimal method for diagnosing an FFPS injury?
6. What are the recommended treatment approaches for an FFPS injury?

STATE OF KNOWLEDGE

Anatomy of the flexor pulley system

There are five annular pulleys in each finger, labeled A1 through A5, and three in the thumb, labeled A1 through A3. These pulleys are named based on their position relative to the bones and joints of the fingers (Figure 1) [11,12].

- **A1 Pulley**: Located at the level of the metacarpophalangeal (MCP) joint, this pulley is anchored to the volar plate of the MCP joint.
- **A2 Pulley**: Situated on the proximal phalanx, this is one of the most important pulleys for preventing bowstringing. It is directly connected and attached to the bone structure, forming a strong and stable bond.
- **A3 Pulley**: Found at the level of the proximal interphalangeal (PIP) joint, this pulley is also connected to the volar plate of the PIP joint.
- **A4 Pulley**: Located on the middle phalanx, it is another critical pulley that anchors the tendon close to the bone.
- **A5 Pulley**: Positioned at the level of the distal interphalangeal (DIP) joint, this pulley is less significant compared to A2 and A4, but still plays a role in tendon guidance [11,12,13,14].

The cruciate pulleys (C1, C2, and C3) are thinner, more flexible structures that lie between the annular pulleys. They cross over each other, allowing the flexor tendon sheath to collapse and expand smoothly during finger flexion and extension [15,16].

- **C1 Pulley**: Located between the A2 and A3 pulleys.
- **C2 Pulley**: Positioned between the A3 and A4 pulleys.

- **C3 Pulley**: Found between the A4 and A5 pulleys [16,17].

The thumb has a similar but simplified pulley system compared to the fingers. It includes the **A1 pulley**: located at the MCP joint, the **oblique pulley**: situated on the proximal phalanx, it is crucial for thumb flexion, the **A2 pulley**: located at the level of the interphalangeal (IP) joint [18,19].

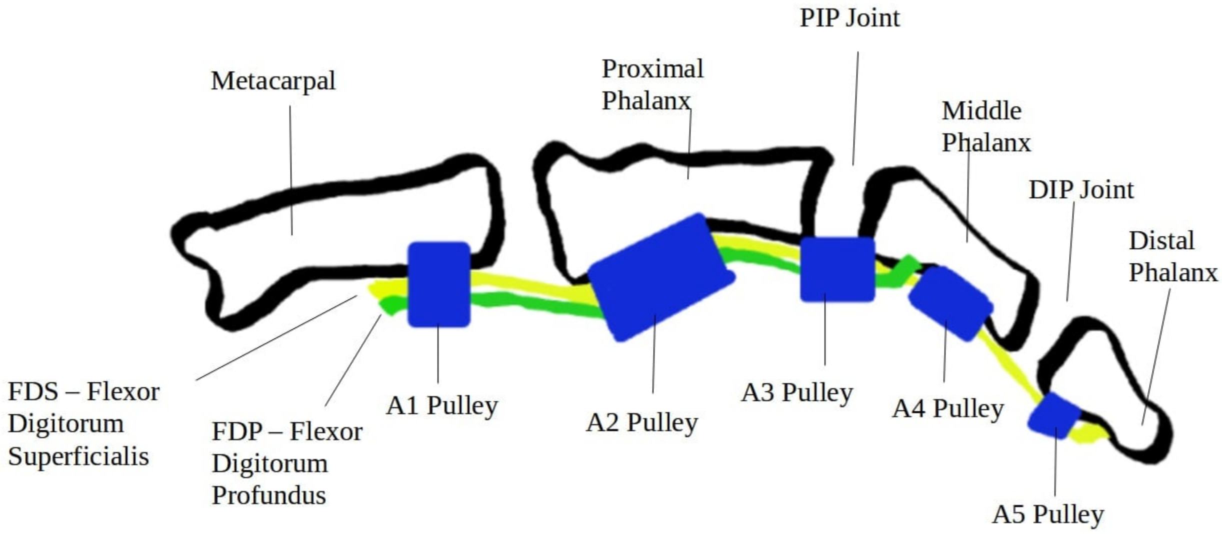

Figure 1 Anatomy of the finger flexor pulley system (FFPS).

Function of the flexor pulley system

The flexor pulley system performs several essential functions that are vital for the dexterity and strength of the hand. These functions include preventing bowstringing, optimizing mechanical advantage, facilitating smooth tendon gliding, and maintaining joint stability. Bowstringing occurs when the flexor tendons move away from the bones, creating a visible and functional gap. This condition reduces the efficiency of finger flexion and significantly decreases grip strength. The flexor pulleys prevent bowstringing by holding the tendons close to the phalanges, ensuring that the force generated by the muscles is transmitted directly to the fingertips. The flexor pulley system enhances the mechanical advantage of the flexor tendons. By maintaining the tendons close proximity to the bones, the pulleys allow for more effective force transmission during finger flexion. This positioning increases the leverage of the tendons, making movements more powerful and precise. The pulleys form a tunnel through which the flexor tendons glide as the fingers flex and extend. This tunnel minimizes friction and allows the tendons to move smoothly. The cruciate pulleys, in particular, provide the necessary flexibility for the tendon sheath to expand and contract without causing irritation or damage to the tendons. The flexor pulleys contribute to the stability of the finger joints by maintaining the alignment of the tendons and preventing dislocation. This stability is crucial for the fine motor control required for complex tasks such as writing, typing, and manipulating small objects. The biomechanics of the flexor pulley system can be appreciated by examining the interaction between the pulleys, tendons, and muscles during finger movements. The flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP) are the primary muscles involved in finger flexion. When the FDS and FDP contract, they pull on the tendons, causing the fingers to flex. The flexor pulleys ensure that the tendons remain close to the bones, providing a direct path for the force to be transmitted from the muscles to the fingers. This alignment maximizes the efficiency of the movement, allowing for strong and controlled flexion. The A2 and A4 pulleys are particularly important for force transmission. They anchor the tendons at critical points along the phalanges, preventing bowstringing and maintaining the mechanical advantage. Without these pulleys, the tendons would bowstring, resulting in a loss of force and a significant decrease in grip strength. Smooth tendon gliding is essential for efficient finger movement. The pulleys create a low-friction environment that allows the tendons to slide easily as the fingers flex and extend. This gliding mechanism reduces wear and tear on the tendons and pulleys, preventing injuries and ensuring the longevity of the hand's functional capabilities [20,21,22,23].

Mechanism of injury

The upper extremities frequently bear the majority of the climber's weight, distributed across several fingers concurrently. Injuries can impact tendons, tendon sheaths, and bones, such as fractures, sprains, and FFPS injuries, which will be the main focus of our attention. Specifically, the crimp grip is employed in rock climbing to optimize finger contact with small surface area climbing holds, potentially leading to FFPS injuries [24,25]. The crimp grip involves the flexion of the PIP joints at approximately 90 degrees with the DIP joints extended, placing substantial stress on the FDP and FDS as they contract to align the fingers with the body weight (Figure 2). The resultant forces on the FDP and FDS, in conjunction with PIP flexion, are counteracted by the flexor tendon pulleys as they flex against resistance. Notably, the A2 pulley experiences the greatest tension, reaching forces up to four times higher than those experienced by the distal phalanges [26,27,28,29]. Consequently, the clenched grip position is linked to increased likelihood and severity of physiological pulls, with the ring finger being the most commonly affected, followed by the middle finger. Single A2 pulley tears constitute the most frequently reported serious finger injuries. Investigations indicate that pulley failure is likeliest to occur under eccentric loading. It is imperative to recognize that pulleys do not possess muscular characteristics; hence, eccentric loading refers to the direction of finger movement, such as extension resulting from sudden hand opening [26,28,30,31].

In the study conducted by Vigouroux et al., an examination of the forces acting on tendons and pulleys during diverse grips in a sports clamp was undertaken. The research revealed that the flexor digitorum profundus (FDP) played a primary role in finger flexion during the crimp grip, while in the slope grip, the tension in the tendons was evenly distributed between FDP and flexor digitorum superficialis (FDS). Additionally, the forces exerted on the pulleys were observed to be 36 times lower for A2 and 4 times lower for A4 in the "slope" grip in comparison to the "crimp" grip [32].

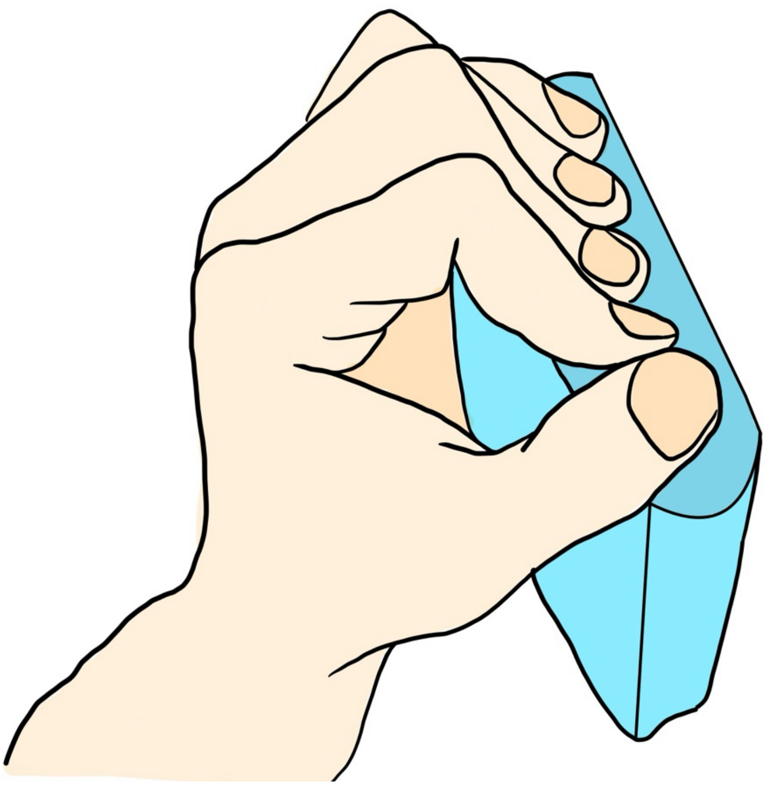

Figure 2 The crimp grip.

Diagnosis and symptoms

Individuals who have sustained injuries to the Flexor Digitorum Profundus (FDP) finger's flexor pulley system (FFPS) often present symptoms such as swelling, pain, numbness, and hematoma in the affected region. Some patients also report a clicking sound when reaching for a hold, with many disregarding these indications and persisting with climbing activities for an extended duration. Additionally, observable bowstringing over the palmar surface of the joint further signifies potential FFPS injuries [33,34,35]. When the tendon is shortened through bowstringing, it does not reach its full shortening potential during muscle contracture. As a result, this incomplete shortening leads to a loss of power and function. The normal course of the tendon is altered due to this incomplete shortening, which in turn increases the functional length of the tendon. This ultimately results in an active flexion deficit [36]. While these symptoms may aid in the preliminary diagnosis of FFPS injuries, definitive conclusions necessitate the performance of imaging tests. In the initial phase of diagnosing hand injuries, it is advisable to conduct an X-ray examination to rule out phalangeal fractures. Subsequently, ultrasound imaging emerges as the preferred modality due to its widespread availability and cost-effectiveness. Nonetheless, the effectiveness of ultrasound is contingent upon the operator's proficiency and is limited by the ultrasound head's capacity to fully assess the proximal interphalangeal (PIP) joint flexion [29]. During an ultrasound examination, the tendons exhibit hyperechoic characteristics, while the palmar surfaces of the pulley encapsulating the flexor tendons display similar hyperechoic features, whereas the lateral surfaces appear hypoechoic in nature [37,38]. Diagnosis of A2 and A4 pulley strains is established when the separation between the tendon and bone measures less than 2 mm, whereas ruptures are indicated when the measurement exceeds this threshold. Furthermore, a distance of more than 0.9 mm between the palmar plate and the flexor tendons signifies a rupture of the A3 pulley [39]. In musculoskeletal soft tissue injuries, particularly those associated with FFPS injuries, magnetic resonance imaging (MRI) serves as a valuable diagnostic tool. MRI can detect specific abnormalities indicative of FFPS injuries, such as the separation of the flexor tendon from the bone, discontinuity of the pulley tendon, hematoma formation between the phalanx and flexor tendon, and displacement of the flexor tendon on the side of the fracture. When ultrasound imaging yields inconclusive results in a clinical setting, MRI may be the preferred modality. However, it is important to note that MRI's limitations include its cost and the absence of dynamic imaging capabilities [40,41]. A scale for evaluating pulley injuries was developed to gauge the severity of the injury (Table 1).

Grade	Injury
I	Pulley strain
II	Complete tear of A3 or A4, partial tear of A2
III	Complete tear of A2
IVa	Multiple ruptures: – A2/A3 or A3/A4 rupture if: – No major clinical bowstring – Ultrasound-proven possibility of reposition of the flexor tendon to the bone – Therapy starting <10 d after injury – No contracture
IVb	Multiple ruptures: – A2/A3 or A3/4 with obvious clinical bowstring – A2/A3/A4 rupture – Singular pulley rupture with FLIP phenomena – Singular rupture with increasing contracture – Singular rupture with secondary, therapy resistant, tenosynovitis

Table 1 Pulley injury grading system. (Schöffl et al.) [41,42,43]

Treatment

Grade I-III pulley injuries are amenable to non-surgical treatment. Treatment modalities encompass the use of anti-inflammatory medications, immobilization, abstinence from climbing activities, physical therapy, and pulley stabilization utilizing various taping techniques and a protective splint. The length of protective therapy and the period for resuming sports activity are contingent upon the extent of pulley damage (Table 2) [41,42,43].

The Pulley Security Splint (PPS) offers a secure method of finger fixation using non-elastic tape, without causing compression of blood vessels or nerves, in contrast to conventional taping techniques. It is recommended to wear the device for 6-8 weeks. This approach facilitates the repositioning of flexor tendons towards an anatomically correct alignment, thereby promoting functional healing of the pulley to a length that closely resembles its original state.

Consequently, this method yields a reduction in tendon-phalanx distance (TPD). Schneeberger et al conducted a study involving 45 mountaineers with complete pulley tears to assess the efficacy of the prescribed protective splint. Evaluation of TPD using ultrasound before and after treatment revealed a consistent decrease in TPD across all treated patients. Subsequently, the vast majority of patients demonstrated restoration of previous levels of dexterity, grip strength, and finger functionality for both climbing and routine daily activities [44].

The application of non-elastic tape is the predominant technique utilized for safeguarding the pulley post-injury. This method serves to both alleviate strain on a previously injured pulley and mitigate the likelihood of further or new injuries. Three distinct taping methodologies are employed: the circumferential approach, the H-tape method, and the figure 8 technique. Taping of the injured finger should be implemented for a duration of 3 months for grade I to III injuries and for a minimum of 12 months for grade IV injuries [41,42,43].

In a study conducted by Schoffl et al., the effects of various banding methods were compared. The H-tape method, which involves encircling the finger at the level of pulley A3, was found to reduce the tendon-to-bone distance by 16% in the injured finger, representing the sole taping approach to achieve a statistically significant difference. Additionally, the H-taping method demonstrated a 13% increase in the strength of injured fingers in the clenched grip position compared to alternative taping methods [45].

In cases of grade IV injuries, the general recommendation is for surgical repair to prevent permanently increased distance from bone to tendon and scarring, which can result in flexion contracture. Recent studies have also demonstrated favorable outcomes with conservative management in IVa ruptures without clinical bowstringing. Surgical repair not only restores the tendon-to-joint relationship but also yields positive biomechanical results. Various pulley reconstruction techniques have been outlined, including the "belt-loop", "single loop", "loop and a half", “double loop” and "triple loop" techniques. The techniques comprise the direct repair of fibrous tissue, as well as the utilization of the long toe autograft for reconstruction purposes. In cases requiring surgery, the affected finger should be immobilized and splinted for a minimum of 2 weeks [42,43].

Oeckenpohler et al conducted a study on patients who had undergone pulley reconstruction using a double- or triple-loop technique. Data from before and up to 4.5 years after reconstruction were compared to the functional hand and included, among others, the NRS pain scale, ROM, vigorimetry, and crimp grip. Surgical intervention improved all final outcomes and can be considered an effective therapeutic option [46].

Mallo et al. conducted a cadaveric reconstruction of the A2 pulley using a minimally invasive double-anchor technique featuring the long palmaris tendon. Comparative analysis of its endurance and strength against the single loop and double loop techniques did not reveal any significant disparities. The primary advantage of the minimally invasive technique lies in its ability to avoid circumferential cutting of the soft tissues, thereby mitigating reconstruction-related injuries [47].

In their study, Soulii et al. conducted a comparative analysis of surgical techniques utilized in the repair of the A2 and A4 trochlea. They evaluated the outcomes of complete excision of A2 and A4, repair of A2 using one ring of tendon graft, repair of A2 with two rings, and repair of A2 with two rings combined with repair of A4 using one ring. Results indicated that all repair interventions led to an increase in mean flexion at the PIP and metacarpophalangeal joints compared to unrepaired specimens. Notably, the 3-ring technique demonstrated the most favorable outcomes, evidenced by a 17% reduction in the PIP angle and a 4% reduction in the metacarpophalangeal angle when compared to the control group. Moreover, the 2-ring technique outperformed the 1-ring technique, and both repair modalities yielded superior results in comparison to the unrepaired samples [48].

	Grade I	Grade II	Grade III	Grade IVa	Grade IVb
Funcional therapy with pulley protection	2–4 weeks H-tape (during daytime) or thermoplastic ring (pulley protection splint)	6 weeks thermoplastic pulley ring (pulley protection splint)	6–8 weeks thermoplastic pulley ring (pulley protection splint)	8 weeks thermoplastic pulley ring (pulley protection splint)	4 weeks thermoplastic ring (after 2 weeks of immobilization)
Easy sport specific activities	After 4 weeks	After 6 weeks	After 8 weeks	After 10 weeks	After 4 months
Full sport specific activities	After 6 weeks	After 8-10 weeks	After 3 months	After 4 months	After 6 months
H-taping during climbing	3 months	3 months	3 months	>12 months	>12 months

Table 2 Therapeutic guidelines. (Adapted by Lutter et al., modified after Schöffl et al.) [42,43,49]

CONCLUSION

FFPS stands as the most commonly diagnosed overuse injury in climbers. The incidence of FFPS-related injuries has risen in the last two decades, attributed to the continued expansion and popularity of the sport. The crimp grip, in particular, poses a high risk due to the extreme forces it generates on the A2 and A4 pulleys. Understanding the mechanisms of these injuries, along with effective diagnostic and treatment strategies, is essential for managing and preventing pulley injuries in climbers. Clinical assessment involves identifying pulley tenderness and, occasionally, bowstring. Imaging studies are imperative for diagnosis and to assess injury severity. Ultrasonography is the preferred imaging modality for suspected FFPS damage, offering direct dynamic visualization of the structures. In cases where ultrasound results are inconclusive, magnetic resonance imaging is recommended as a supplementary imaging option. X-rays are valuable to exclude fractures. Conservative treatment is generally prescribed for grade I to III injuries, while for grade IVa injuries, conservative management may also be suitable. Surgical intervention is indicated for grade IVb injuries. Following an injury, utilizing a splint to safeguard the pulleys or employing H-taping on the fingers can mitigate the risk of subsequent injuries and furnish adequate support for compromised pulleys.

DISCLOSURE

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