Morphological and Biomechanical Study of the Pulley System of the Thumb

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Abstract

The purpose of this study was to define more precisely the anatomy of the thumb flexor pulley system and to determine the relative contribution of each of the pulleys to the biomechanics of thumb motion at the metacarpophalangeal (MP) and interphalangeal (IP) joints. For this, 22 hands from 11 cadavers were used and randomly assigned to two groups. In the first group, the first annular (A1) pulley was cut first followed by the variable annular (Av) pulley and then the oblique pulley. In the second group, the oblique pulley was cut first followed by the A1 pulley and then the Av pulley. In 7 of 22 hands, it was a transverse structure parallel to the A1 pulley with a gap between the A1 and Av pulleys, referred to here as type I. In 9 hands, the A1 and Av pulleys were connected without any gap (type II). In 6 hands, the space between the A1 and Av pulleys were triangular in shape with fibers of the Av pulley converging toward the radial side (type III). In biomechanical study of both first and second experiments, there was no significant difference in MCP joint flexion between the all intact, A1 section, A1/Av section, A2 intact (A1/Av/oblique section), and no pulley configuration (p>.05). In occurring displacements less than 10 ㎜, there was no significant difference in IP joint flexion (p>.05). However, there was a significant decrease in IP joint flexion occurred in both 15 ㎜ and 20 ㎜ excursion (p<.05), when the oblique pulley was resected additionally after cutting the A1 and Av pulleys in first experiment, and when the A1 pulley was resected additionally after cutting the oblique pulley. According to the results, the injury of only the oblique pulley does not decrease thumb motion significantly. The oblique pulley injury with both the A1 and Av pulleys laceration decreased thumb motion significantly. The additional laceration of the A2 pulley does not decrease thumb motion.

Key Words: Biomechanics; Flexor pulley system; Thumb.

Introduction

In the hand function, the thumb is very important and is generally considered to be the most important single digit in hand. Flexion of thumb was affected by flexor pollicis longus tendon and flexor pollicis brevis tendon. Control of delicate movement and grasp of thumb is possible through their normal function. Flexor tendons transmit force from the muscle belly to the thumb to produce motion. Excursion, the distance that the tendon slides along its path, is limited by how much the muscle to which it is attached can be shortened. Excursion of a tendon can be affected adversely by extrinsic fac-

tors, such as contracture and adhesion, and enhanced by exercise or stretching (Goodman and Choueka, 2005). The flexor tendon sheath is composed of synovial and reticular tissue components, which have separate and distinct functions. The membrane portion is a synovial tube sealed at both ends. The reticular or pulley portion is a series of transverse, annular, and cruciform fibrous tissue condensation, which overlay the synovial portion of the sheath (Doyle, 1988). The flexor pulley systems of both the fingers and the thumb facilitate accurate tracking of the tendons, prevent bowstring, and provide a biomechanically efficient fulcrum for flexion and extension of the digit (Doyle, 2001; Hauger et al, 2000; Lin et al, 1989).

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Damage to part or all of the digit flexor pulley system can have a substantial effect on the performance of the digit (Low et al, 1998). Restoration of hand function following flexor tendon injury has been one of the most difficult problems in hand surgery (Luo et al, 2005). In the study of the flexor tendon of the thumb, Doyle and Blythe (1977) reported the pulley system of the thumb had one oblique and two annular pulleys (A1 and A2). In their sectional experiments, significant changes in thumb joint motion were shown only when both the first annular (A1) pulley and oblique were resected. They concluded that the oblique pulley is the most important pulley in the thumb and facilitates the full excursion of the flexor pollicis longus. Zissimos et al (1994) quantified the biomechanical contribution made by each pulley on the mechanical efficiency and angular joint displacement of the thumb. They showed that when both the A1 and the oblique pulleys were cut, considerable bowstringing of the flexor pollicis longus was observed. In a recent anatomic study, Schmidt and Fisher (1999) showed that the original anatomic arrangement of the pulley system of the thumb described by Dolye and Blythe (1977) was found in only 10% of specimens. In 90% of the specimens a Y-shaped fiber complex was identified between the A1 and A2 pulleys.

About the proximal or first annular pulley, some studies reported that only the A1 pulley exists (Allan, 2005; Dolye and Blythe, 1977; Zissimos et al, 1994), but the other represented that the proximal annular pulley had the A1 and the variable annular (Av) pulleys (Bayat et al, 2002). The latter study reported that thumb pulley system had following four pulleys; the A1, the Av, the oblique, and the second annular (A2) pulleys, and then the thumb pulley system was divided into three types by anatomic arrangement.

Thus, until now, there are little studies about thumb pulley system, and each report has not coincided about thumb pulley system. In addition, the contribution of the Av pulley in thumb flexion has not been reported. Therefore, this study was performed to elucidate more precisely, the anatomy of the thumb flexor pulley system and to determine the relative biomechanical contribution of each of the pulleys including the Av pulley at the MCP and IP joints.

Methods

Subjects

Twenty two hands obtained from eleven cadavers (6 men and 5 women) were used for this study. In these hands, there were no pathological changes in both bones and joints. The age of the cadavers ranged from 38 to 83 years (average, 63.5 years).

Instrumentations & Procedures

Hands of each cadaver set palm up, were drawn a line on thumb phalanx and thenar eminence, and were dissected. Skin and fascia were eliminated to show flexor pollicis longus tendon. After confirming all pulleys system in thumb are intact, 22 hands were randomly assigned to one of two groups. In each group, the range of motion of the thumb was measured with all pulleys intact, one pulley resected, two pulleys resected, three pulleys resected, and all pulleys resected. In the first group, the A1 pulley was cut first followed by the Av, the oblique, and then the A2 in that order. In the second group, dissection took place in the order of oblique pulley, A1 pulley, Av pulley, and lastly A2 pulley. These sequences were chosen to identify the relative importance of the pulleys.

Flexor pollicis longus tendon of thumb was pulled on the basis of distal wrist crease at intervals of 5 ㎜ for 20 ㎜. Pins were fixed proximally on the basis of distal wrist crease at intervals of 5 ㎜ for 20 ㎜. Range of motion of MCP and IP joint was measured by goniometer[1]. The width of each pulley was recorded using a fine caliper.

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1) JAMAR, Jackon Co., USA.

Statistical Analysis

The statistical analysis of data was performed using SPSS 10.0. All values are expressed as mean±SD. One-way analysis of variance was used to examine the differences, and a post-hoc test was performed with LSD. The level of significance was set at p<.05.

Results

1. Anatomic Study

As a result of investigating on thumb pulley system of 22 hands, the following four pulleys have been identified: three annular pulleys and one oblique pulley. Two annular pulleys including the proximal or A1 pulley and the variable or Av pulley are located proximal to the oblique pulley with one annular pulley lying distally.

Proximal or A1 pulley was entirely transverse retinacular pulley, and its proximal two thirds were at the level of the volar plate at the metacarpophalangeal joint with the distal one third covering the base of the proximal phalanx. The average width of the A1 pulley was 6.7 ㎜.

The variable or Av pulley, which was 5.8 ㎜ in thickness was similar to that of the A1 pulley (Table 1). The Av pulley covered most of the proximal half of the shaft of proximal phalanx. It originated from the ulnar side of the proximal phalanx at the level of the musculotendinous junction of the adductor pollicis muscle and passed across to attach to the radial side of the proximal phalanx. It varied in

Table 1. Measurements of the pulleys in thumb

Pulley (N)	Width	Range
The A1 pulley (22)	6.7±1.5[a]	3.9~9.4
The Av pulley (20)	5.8±1.2	3.3~7.8
The oblique pulley (21)	4.2±1.2	2.7~6.5
The A2 pulley (22)	7.1±2.2	3.8~10.9

[a]Mean±SD

appearance from a transverse retinacular to an oblique structure. Three distinct morphological arrangements for the pulley system of the thumb were identified (Figure 1) (Figure 2) (Figure 3).

The oblique pulley originated from the ulnar side of the proximal half of the proximal phalanx and inserted to the radial side of the base of the distal phalanx. The average width of the oblique pulley was approximately 4.2 ㎜, five Av pulleys showed a cruciate form or a Y-shape between the oblique and A2 pulleys.

The distal or A2 pulley was lying proximal to the insertion of the flexor pollicis longus. The proximal two thirds of the A2 pulley covered the head of the proximal phalanx and the volar plate of the interphalangeal joint, whereas the distal third of A2 covered the base of the distal phalanx of the thumb. Its average width was 7.1 ㎜.

Three distinct anatomic arrangements for the pulley system of the thumb were classified by the base of previous study (Bayat et al, 2002). In seven of twenty two hands, it was a transverse structure parallel to the A1 pulley with a gap between the A1 and Av pulleys, referred to here as type I. In nine hands, the A1 and Av pulleys were connected without gap (type II). Of these, two hands had no the Av pulley, these two pulleys were included in type II, assuming the Av and A1 pulleys are combined as one. In six hands, the pulley was triangular or purely oblique in shape with its fibers converging toward the radial side (type III).

2. Biomechanical Study

To investigate the importance of each pulley, they were cut in the following order of the A1, the Av, the oblique, and the A2 pulleys, in first experimental group. In MCP joint, there wasn't any significance in excursion between the all intact, A1 section, A1/Av section, A2 intact (A1/Av/oblique section), and no pulley configuration (p>.05) (Figure 4A). In IP joint, there was also no significant difference in IP joint flexion occurring at all displacements of both at 5 ㎜ and 10 ㎜ regardless of pulley section.
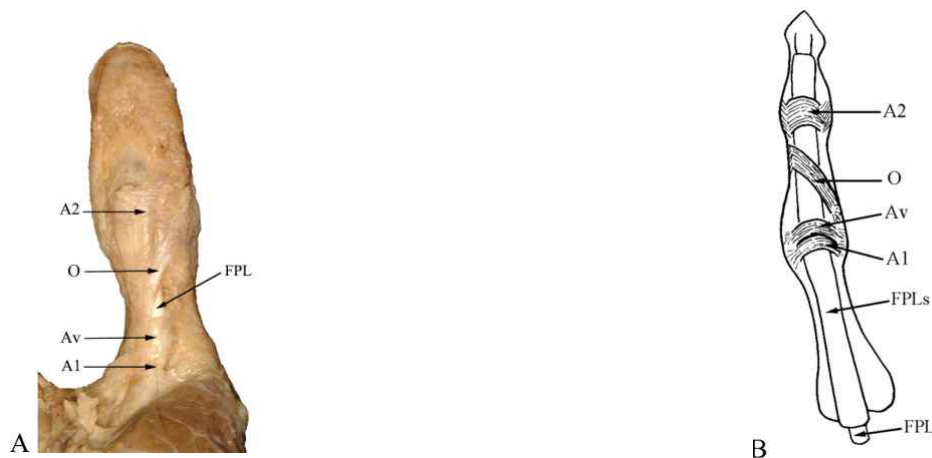
Figure 1. Type I pulley system of the left thumb. Photograph (A) and diagram (B) of the pulley system. A1: the proximal annular pulley, Av: the variable pulley, O: the oblique pulley, A2: the distal annular pulley, FPL: flexor pollicis longus tendon, FPLs: flexor pollicis longus tendon sheath


Figure 2. Type II pulley system. Photograph (A) of the right thumb and diagram of the left thumb (B) of the pulley system. A1: the proximal annular pulley, Av: the variable pulley, O: the oblique pulley, A2: the distal annular pulley, FPL: flexor pollicis longus tendon, FPLs: flexor pollicis longus tendon sheath

However, there was a significant decrease in IP flexion occurring in 15 ㎜ excursion (p<.05) (Figure 5A), when the oblique pulley was resected additionally after cutting A1 and Av. In case of the displacement at 20 ㎜, there was also a significant decrease in IP joint flexion in additional the oblique pulley section, after cutting A1 and Av pulleys. There was no significant difference between having only A2 pulley and no pulleys intact (Figure 5A) (p<.05).

In the second experiment to investigate the importance of the oblique pulley, there was no significant difference in MCP flexion between the all intact, oblique section, oblique/A1 section, oblique/A1/Av section, and no pulley configuration (Figure 4B). In IP joint, a significant decrease in IP joint flexion occurred at displacement from 10 ㎜ to 20 ㎜ (p<.05) (Figure 5B). Displacement of only 10 ㎜ showed a significant difference in IP joint flexion

Figure 3. Type Ⅲ pulley system of the left thumb. Photograph (A) and diagram (B) of the pulley system. A1: the proximal annular pulley, Av: the variable pulley, O: the oblique pulley, A2: the distal annular pulley (dissected in A), FPL: flexor pollicis longus tendon, FPLs: flexor pollicis longus tendon sheath
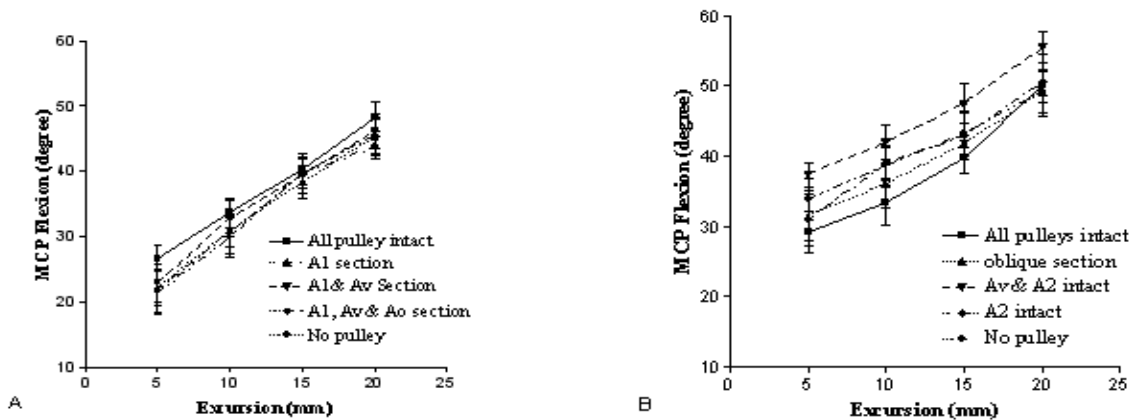
Figure 4. Metacarpophalangeal (MCP) flexion of flexor pollicis longus tendon excursion

between the all pulley intact and no pulley, in second experiment group (p<.05). There was no significant difference in IP joint flexion between all pulleys intact and the oblique pulley section. It represented that only the oblique pulley injury did not affect on IP joint flexion. There was no significant difference in IP flexion between only A2 intact and no pulley (Figure 5B). It showed that the A2 pulley did not affect on IP joint flexion.

In both first and second experiments, there was no significant difference in MCP flexion between the all intact, A1 section, A1/Av section, A2 intact (A1/Av/oblique section), and no pulley configuration (p>.05).

In occurring displacements less than 10 ㎜, there was no significant difference in MCP and IP flexion except for significant difference in IP flexion between all pulleys intact and no pulley in second experiment (Figure 4) (Figure 5).
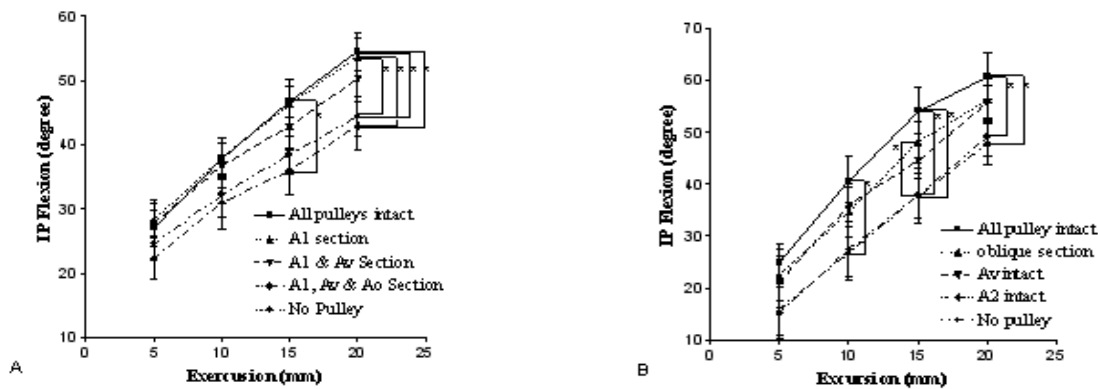
Figure 5. Interphalangeal (IP) flexion as a function of flexor pollicis longus tendon excursion

Discussion

A comprehension of the morphology and the bio-mechanics of the flexor tendon system are funda-mental to proper evaluation and treatment of disorder of the hand (Goodman and Choueka, 2005). Significant advances in the understanding of intra-synovial flexor tendon repair and rehabilitation have been made since the early 1970s (Kessler and Nissim, 1969; Verdan, 1972). However, these advances was usually focused at flexor tendon and flexor sheaths of four digits except for the thumb. In spite of im-portance of the thumb in hand function, the studies about the thumb pulley system is not enough.

In morphological studies of the thumb pulley sys-tem, some studies showed that the thumb pulley system has the A1, oblique, and A2 pulleys (Allan, 2005; Dolye and Blythe, 1977; Zissimos et al, 1994) However, Bayat et al (2002) showed the Av pulley additional to the A1, oblique, and the A2 pulleys. This present study has also identified the Av pulley between A1 and the oblique pulleys of the thumb. the A1, the Av, the oblique, and the A2 pulleys had the following respective widths measured in ex-tension: 4 to 9 ㎜, 3 to 8 ㎜, 3 to 7 ㎜, and 4 to 11 ㎜. Bayat et al (2002) reported, comparing his report with Doyle and Blythe (1977), that pulley width dis-crepancy in both of their studies could be explained by the fact that the width of the oblique pulley, re-ported by Doyle and Blythe (1977), was nearly equivalent to the width of both the Av and the obli-que pulley in his study, suggesting Doyle and Blythe (1977) regarded these as a single structure. The thickness of the Av pulley was similar to that of both the A1 and oblique pulleys. The result of this study also supports the suggestion of Bayat et al (2002) due to the width of the oblique pulley, re-ported by Doyle and Blythe (1977), was nearly equivalent to the width of both the Av and the obli-que pulley in Doyle and Blythe's study. Schmidt and Fischer (1999) showed that the original anatomic ar-rangement of the pulley system of the thumb de-scribed by Doyle and Blythe (1977) was found in only 10% of their specimens. In 90% of the speci-mens, a Y-shaped fiber complex was identified be-tween the A1 and A2 pulleys. As such, Schmidt and Fischer (1999) showed not only the existence of the Av pulley, but also substantial variations in its con-formation with 3 types being clearly defined. In this study, three Av pulleys showed a cruciate or a Y-shape found in only 23% of the total. This discrep-ancy would be considered that the study by Schmidt and Fischer (1999) did not classify the Av pulley be-tween the oblique and A1 pulleys, but the Av pulley was regarded as a part of the oblique pulley.

The distance from the joint axis to tendon affects on force applying joint, and this distance is called a "moment arm". A function of the flexor pulleys is

to maintain a near constant moment arm of the flexor tendons. In a damaged or ruptured pulley, the force of the contracting muscle causes the tendon to "pull away" from the joint axis of rotation, a phenomenon called "bowstringing" of the tendon. Bowstringing of a tendon significantly increases the internal moment arm of the tendon and, in turn, increases the mechanical advantage of the muscle. As the mechanical advantage of the muscle increases, the torque produced per level muscle force amplifies, but on the other hand, the angular rotation of the joint reduces (Neumann, 2002). In mechanical studies of the thumb pulley, Dolye and Blythe (1977) reported that significant changes in thumb joint motion occurred only when both the first annular pulley and oblique are resected. In this instance, motion was lost at the IP joint and gained at the MCP joint with little change in the total arc of motion. They concluded that the oblique pulley was necessary to restore normal tendon function in the event of thumb injury. It is considered that Dolye and Blythe (1977) would not consider both the A1 and the Av pulleys, separately, as the A1 pulley.

Zissimos et al (1994) suggested that repair of either the A1 or oblique pulley suffices to restore normal thumb kinematics. Other biomechanical studies showed that an intact oblique or A1 pulley could equally maintain normal excursion of the flexor pollicis longus tendon and the function of the thumb (Doyle and Blythe, 1977; Esplin et al, 1996; Lin et al, 1989). Therefore, if only one of these two pulleys is injured, surgical repair or reconstruction of the deficit is probably unnecessary in most cases. They suggested these findings indicated that repair or reconstruction of either the A1 or oblique pulley after injury would restore normal thumb kinematics. This present study also showed injury in either the A1 or oblique pulley did not affect with flexion at MCP and IP joints. There were no studies about mechanics of the Av pulley, this study shows Av pulley did not affect the movement of both MCP joint and PIP joint significantly. This result may show because the

Av pulley is located between the A1 and oblique pulleys. Doyle and Blythe (1977) reported on the A2 pulley that if the oblique pulley was intact, then loss of the A2 pulley did not result in significant loss of motion. Zissimos et al (1994) showed there was no statistical difference between the isolated, intact A2 pulley and no intact pulleys. This study also shows there were no significant difference between intact the A2 pulley and no intact pulleys.

In flexion values for the carpometacarpal (CMC), MCP and IP joints of the thumb, flexion is greatest at the IP and least at the CMC joint. MCP and IP joint flexion of the thumb were 54~57 degrees and 80 degrees, respectively (De Smet et al, 1993; Skvarilova and Plevkova, 1996). In this study, when the flexor pollicis longus tendons were pulled by 20 ㎜, there was a flexion approximately from 50 to 60 degrees at MCP and IP joint. Differences in MCP joint flexion would be caused by the use of cadavers fixed by formalin. The sum of MCP and IP motion, or total arc of motion, did not change significantly at any given displacement, regardless of the pulley configuration. As any two or more pulleys were resected, motion lost at the IP joint was gained at the MCP joint. Bowstringing occurred only after both the A1 and oblique pulleys were resected (Zissimos et al, 1994).

This study has relevance to the treatment of trigger thumb and in pulley reconstruction. It is also proposed that repair or reconstruction of either the A1 pulley or the Av pulley would be sufficient to restore the normal motion of the thumb, and prevent bowstring of the flexor pollicis longus tendon. This study would ultimately help to evaluate the relative function of the A1 and Av pulleys in more detail. There is a need of further studies in larger samples to confirm this result using fresh-frozen cadavers.

Conclusion

This study was done to investigate the morphology and mechanics of the pulley system of the

thumb. As a result of investigating on thumb pulley system of twenty two hands, the following four pulleys have been identified: three annular (A1, Av, and A2) pulleys and one oblique pulley. The pulley system of the thumb was classified by the configuration of the Av pulley into three types. The type I found in 7 of 22 hands (32%) that the Av pulley was parallel to A1 with a gap between the A1 and Av pulleys. The type II revealed in 9 hands (41%) that the A1 and Av pulleys were connected without gap. The type III showed in 6 hands (27%) that the Av pulley was oblique in shape.

Only one Injury of either the A1 or the oblique pulley does not affect flexion at MCP and IP joints. The additional the Av pulley section after the A1 pulley section does not significantly decrease flexion values at MCP and IP joints. At least concomitant injuries of the A1, the Av, and oblique pulleys have to occur for the flexion to decrease significantly at MCP and IP joints.

References

Allan CH. Flexor tendons: Anatomy and surgical approaches. Hand Clin. 2005;21(2):151-157.

Bayat A, Shaaban H, Giakas G, et al. The pulley system of the thumb: Anatomic and biomechanical study. J Hand Surg. 2002;27(4):628-635.

De Smet L, Urlus M, Spriet A, et al. Metacarpophalangeal and interphalangeal flexion of the thumb: Influence of sex and age, relation to ligamentous injury. Acta Orthop Belg. 1993;59(4):357-359.

Doyle JR. Anatomy of the finger flexor tendon sheath and pulley system. J Hand Surg (Am). 1988;13(4):473-484.

Doyle JR. Palmar and digital flexor tendon pulleys. Clin Orthop Relat Res. 2001;383:84-96.

Doyle JR, Blythe WF. Anatomy of the flexor tendon sheath and pulleys of the thumb. J Hand Surg (Am). 1977;2(2):149-151.

Esplin VS, Tencer AF, Hanel DP, et al. Restoration of function of the thumb flexor apparatus requires repair of the oblique and one adjacent flexor tendon pulley. J Orthop Res. 1996;14(1):152-156.

Goodman HJ, Choueka J. Biomechanics of the flexor tendons. Hand Clin. 2005;21(2):129-149.

Hauger O, Chung CB, Lektrakul N, et al. Pulley system in the fingers: Normal anatomy and stimulated lesions in cadavers at MR imaging, CT, and US with and without contrast material distension of the tendon sheath. Radiology. 2000;217(1):201-212.

Kessler I, Nissim F. Primary repair without immobilization of flexor tendon division within the digital sheath. An experimental and clinical study. Acta Orthop Scand. 1969;40(5):587-601.

Lin GT, Amadio PC, An KN, et al. Functional anatomy of the human digital flexor pulley system. J Hand Surg. 1989;14(1):949-956.

Low CK, Pereira BP, Ng RT, et al. The effect of the extent of A1 pulley release on the force required to flex the digits. J Hand Surg. 1998;23(1):46-49.

Luo J, Mass DP, Phillips CS, et al. The future of flexor tendon surgery. Hand Clin. 2005;21(2):267-273.

Neumann DA. Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation. St. Louis, Mosby, 2002.

Schmidt H-M, Fischer G. Pulleys of the tendon sheath of the flexor pollicis longus muscle. Handchir Mikrochir Plast Chir. 1999;31(6):362-366.

Skvarilova B, Plevkova A. Ranges of joint motion of the adult hand. Acta Chir Plast. 1996;38(2):67-71.

Verdan CE. Half a century of flexor-tendon surgery. Current status and changing philosophies. J Bone Joint Surg (Am). 1972;54(3):427-491.

Zissimos AG, Szabo RM, Yinger KE, et al. Biomechanics of the thumb flexor pulley system. J Hand Surg. 1994;19(3):475-479.