Journal of Hand Therapy 28 (2015) 347–355

Contents lists available at ScienceDirect

Journal of Hand Therapy

journal homepage: www.jhandtherapy.org

JHT Read for Credit Article #383.

Scientific/Clinical Article

Effect of wrist and interphalangeal thumb movement on zone T2 flexor pollicis longus tendon tension in a human cadaver model

Patricia O. Rappaport PT, CHT[a], Andrew R. Thoreson MSc[a], Tai-Hua Yang MD[a], Ramona L. Reisdorf BS[a], Stephen M. Rappaport PhD[b], Kai-Nan An PhD[a], Peter C. Amadio MD[a,*]

[a] *Tendon and Soft Tissue Biology Laboratory and the Biomechanics Laboratory, Mayo Clinic, Rochester, MN, USA*
[b] *School of Public Health, University of California, Berkeley, Berkeley, CA, USA*

ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form
31 March 2015
Accepted 1 April 2015
Available online 14 April 2015

Keywords:
Flexor pollicis longus
Thumb
Hand therapy
Human
Cadaver
Biomechanics

ABSTRACT

Introduction: Therapy after flexor pollicis longus (FPL) repair typically mimics finger flexor management, but this ignores anatomic and biomechanical features unique to the FPL.
Purpose of the study: We measured FPL tendon tension in zone T2 to identify biomechanically appropriate exercises for mobilizing the FPL.
Methods: Eight human cadaver hands were studied to identify motions that generated enough force to achieve FPL movement without exceeding hypothetical suture strength.
Results: With the carpometacarpal and metacarpophalangeal joints blocked, appropriate forces were produced for both passive interphalangeal (IP) motion with 30° wrist extension and simulated active IP flexion from 0° to 35° with the wrist in the neutral position.
Discussion: This work provides a biomechanical basis for safely and effectively mobilizing the zone T2 FPL tendon.
Conclusion: Our cadaver study suggests that it is safe and effective to perform early passive and active exercise to an isolated IP joint.
Level of evidence: NA.

Introduction

Extensive study of treatment following repair of finger flexor tendons has continued to enhance rehabilitation and outcomes.[1] Although knowledge gained from study of finger flexors is relevant to treating the flexor pollicis longus (FPL), features unique to the opposable thumb[2–4] challenge straightforward extrapolation. Since limited scientific research has been devoted specifically to the FPL,[5–7] the scientific basis for early-phase mobilization following FPL repair may not be fully optimized.

As compared to the fingers, thumb motion involves highly complex patterns of flexion/extension, abduction/adduction, and circumduction. The FPL harnesses this mobility by providing stability, strength, and dexterity.[8–10] As the sole flexor of the interphalangeal (IP) joint, it is essential to thumb opposition and — being independent from the flexors of the fingers — enables the hand to perform highly precise movements crucial to daily function.[8,10] However, lack of interconnections to the fingers leads to higher incidence of proximal tendon retraction following laceration, complicating repair and rehabilitation.[5,7,11,12] Furthermore, while early mobilization is known to enhance healing and tensile strength,[13] the most effective means for introducing early active motion remains controversial[14] and appears to be better established for the finger flexors than for the FPL.

Study of the FPL by Sirotakova, Elliot, and Southgate [5,15,16] has informed surgical techniques and orthosis design, but optimal mobilization methods remain elusive. Using dividers and a 0.5-mm calibrated ruler, Brown and McGrouther[17] found a 70% increase in tendon excursion in zone T2 with isolated passive IP flexion when compared to simultaneous flexion of the IP and metacarpophalangeal (MCP) joints. Although this confirmed that isolating the IP joint produces greater tendon glide, it is unclear whether the forces generated by passive IP flexion can overcome gliding resistance at the site of repair, or whether force generated by active IP flexion might exceed repair strength.

Conflict of interest: All named authors hereby declare that they have no conflicts of interest to disclose.

* Corresponding author. Department of Orthopedic Surgery, Mayo Clinic, 200 1st Street SW, Rochester, MN 55905, USA. Tel.: +1 507 538 1717; fax: +1 507 284 5392.
E-mail address: pamadio@mayo.edu (P.C. Amadio).

0894-1130/$ — see front matter © 2015 Hanley & Belfus, an imprint of Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jht.2015.04.002

It is well understood that wrist position is crucial to treating a repaired tendon.[18] Yet, forces associated with various wrist positions, specifically in combination with isolated thumb IP motion, have not been investigated. Lastly, synergistic motion has been recognized to offer low finger flexor force with high tendon excursion,[19–24] but the influence of synergistic wrist motion on the thumb flexor has not been reported.

To better understand how joint position and mobilization methods optimize the mechanics of FPL rehabilitation, we utilized the concept of a 'safe and effective zone' (SEZ) where the forces applied (actively or passively) are great enough to achieve tendon movement while remaining below those that disrupt the suture repair.[22,25,26] The lower SEZ limit represents the viscoelastic drag of the repaired tendon within its sheath,[27–29] while the upper SEZ limit represents the force a repair can withstand before gapping.[30] Using a modified Kessler suture technique, the SEZ for the FPL was reported to be between 1.3 N[31,32] and 7 N.[22,26] Additionally, it has been suggested that a minimum of 2 mm of tendon excursion at the repair site is needed to minimize adhesions and thus maintain adequate tendon glide for functional motion.[33–35]

In this cadaveric study, we measured the forces acting on the FPL in zone T2 as induced by the tenodesis effect of wrist position while passively moving the isolated IP joint and passively performing a synergistic arc of wrist motion. Then, we experimentally induced a simulated active IP motion while blocking the MCP, carpometacarpal (CMC), and wrist in neutral. We hypothesized that measuring the forces generated under these conditions would identify safe and effective motion, and thereby provide a biomechanically-based guide for post-surgical rehabilitation.

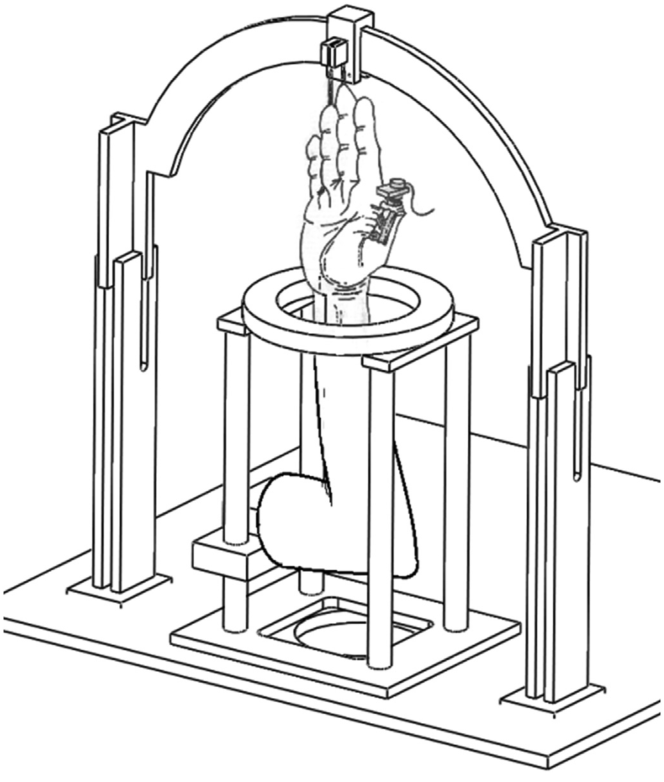

Fig. 1. Kinematic wrist table with load-cell transducer in place on the thumb.

Materials and methods

Subjects

This study was approved by Mayo Clinic Institutional Review Board (IRB) and Biospecimens Subcommittee (Study # 13-008747/Bio00011478). Eight fresh-frozen human forearms (four right and four left), consisting of all tissue distal to the mid-humerus, were obtained from eight different cadavers with a mean age of 77 years (range 55–94 years) through our institution's anatomical bequest program. Specimens were screened for arthritic changes as well as hand and wrist injury. No thumb IP limitations related to arthritis or otherwise, were noted. The sample size of 8 specimens was selected based on a previous study[22] which had 80% power to detect a difference of 15 N in mean tendon forces with a significance level of $\alpha = 0.05$.

Experimental setup

The elbow was fixed at 90° by inserting a K-wire (2.3 mm) through the intramedullary canal of the humerus and the olecranon of the ulna while simultaneously securing the mid-forearm in neutral pronation/supination with K-wire through the radius and ulna. The arm was oriented vertically on a wrist joint kinematic table with the mid-forearm K-wire secured to the table and the distal humerus firmly locked onto the table. To maintain wrist motion in the desired plane, K-wires (1.5 mm) were inserted into the distal, middle, and proximal phalanges and metacarpals of the long and ring fingers. The K-wires were then secured to an arched Plexiglas guide (Fig. 1).

A 2.0-mm K-wire fixed the MCP joint at 0° flexion/extension/abduction/adduction. An external fixator was attached at the CMC joint allowing for reliable adjustment of CMC radial abduction/adduction angles. To mark the IP axis of rotation, a pin was driven into the head of the proximal phalanx at a right angle to the plane of flexion and used to locate the goniometer for measuring IP angle during excursion data collection. A mid-volar incision between the A1 and A2 pulleys allowed for access to the FPL tendon without disrupting the pulley system. With the wrist in a neutral position, IP and MCP joints at 0°, and CMC at 30° radial abduction, a marker suture (6-0 polypropylene) was inserted into the tendon in line with a reference suture placed in tissue firmly attached to the bone. To further assist with visual alignment, an additional reference suture was place in the skin. As seen in Fig. 2, all three sutures were located just proximal to the IP joint. Tendon excursion between the marker and reference sutures was measured with a digital caliper calibrated to 0.5 mm.

Approximately 1.5 cm of the distal phalanx was removed so that a custom-fabricated platform could be press-fit into the intramedullary canal of the remaining distal phalanx. After securing a small button load cell transducer (10804 50 lb. capacity, Entran, Hampton, VA) to the platform, the FPL tendon was cut near its bony insertion and connected to the transducer with 2-0 braided polylactic acid suture (Vicryl; Ethicon, Somerville, NJ). To achieve resting tendon tension, care was made to maintain alignment of the marker and reference sutures.

Thumb IP and wrist joint positions were measured with a three-dimensional motion analysis system (Motion Analysis Corporation, Santa Rosa, CA). For IP motion, two spherical (3-mm diameter) retro-reflective markers were secured to the transducer platform in a parallel orientation to the long axis of the distal phalanx. Two additional reference markers were secured vertically along the proximal phalanx. For wrist motion, three (5-mm diameter) markers in a triangular configuration were secured into the 4th metacarpal and a similar configuration into the distal radius (Fig. 3). Wrist angles and thumb IP flexion angles were captured using three motion capture cameras placed perpendicular to the long axis of the third metacarpal and oriented to maintain focus on the retro-reflective markers during testing.

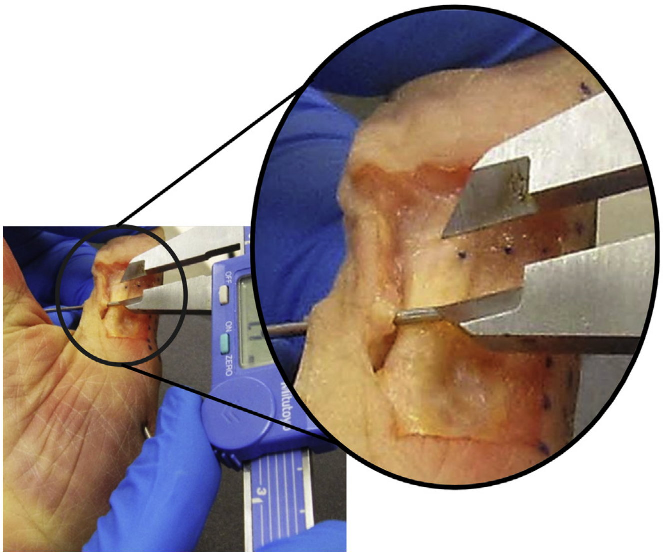

Fig. 2. Digital caliper measured tendon excursion between reference and marker sutures. CMC and MCP joints fixed in neutral to establish isolated IP flexion.

Isolated IP passive motion in combination with wrist positioning

This segment of the experiment was designed to identify which wrist positions, when combined with isolated IP passive motion, would produce optimal force (1.3 N–7 N) across the FPL tendon in zone T2. The wrist positions included: 30° flexion (position 1), 0° neutral (position 2), 30° extension (position 3), 60° extension (position 4), 20° radial deviation (position 5), and 40° ulnar deviation (position 6). At each wrist position, the IP joint was passively moved from 0° to full flexion and back to 0° while force and IP motion were simultaneously captured at a sample rate of 50 Hz. Two warm-up cycles of IP flexion/extension were performed with measurements taken on the third cycle. The operator maintained a near constant rate of joint motion, with each cycle requiring approximately 6–7 s. Experiments were conducted for each of the 6 wrist positions with CMC fixed at either 30° or 40° abduction (a total of 12 configurations). All CMC positions were in the plane of the palm (radial abduction) and measured with the goniometer placed along the 1st and 2nd metacarpals. The MCP joint was fixed at 0° throughout testing. Three trials were recorded for each configuration.

Synergistic wrist motion

While the tenodesis effect on finger flexors has been documented, this experiment focused on how wrist tenodesis flexion/extension and ulnar/radial deviation impacted tension across the FPL in zone T2. With the wrist at 0° and the CMC at 30° abduction, two warm-up cycles of IP flexion and extension were performed and the IP was then allowed to freely relax at 0°. The wrist was moved along the frame guide from 0° to 60° flexion to 60° extension and back to 0° while continuously recording force and reflective marker position of the wrist at a sample rate of 50 Hz. A near constant rate of wrist motion was maintained with a complete cycle requiring approximately 15 s. This experiment was repeated for a wrist motion arc from 0° to 20° radial deviation to 40° ulnar deviation and back to 0°. The same cycles were repeated for the CMC fixed at 40° abduction. Again, the MCP joint was fixed at 0° throughout testing and three trials were performed for each cycle of motion.

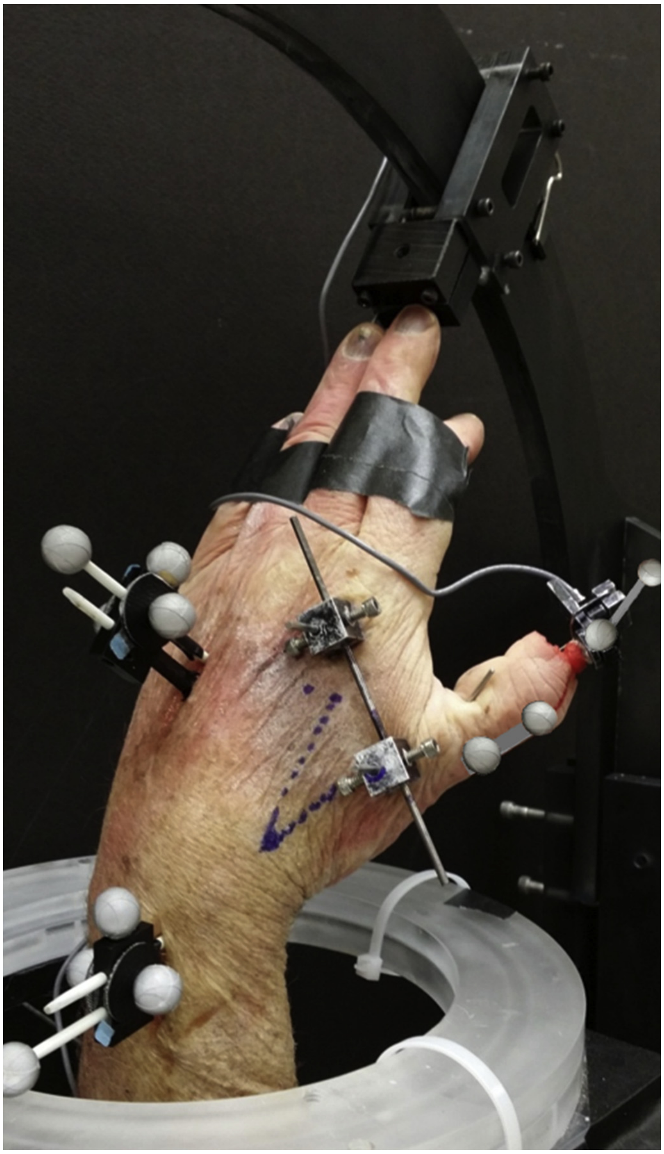

Fig. 3. Setup included reflective markers for tracking motion, an external fixator for CMC angle adjustment, and a press-fit load cell attached to the FPL tendon with suture.

Induced isolated IP active flexion in wrist/CMC/MCP neutral

To achieve isolated IP flexion, the wrist was fixed at 0°, CMC at 30° abduction and MCP at 0°. An additional 10-lb capacity load cell (MDB-10, Transducer Techniques, Temecula, CA) was attached to the FPL tendon just distal to the musculotendinous junction in the distal forearm. While manually pulling the forearm load cell in a proximal direction, the induced IP flexion angles were captured by the motion analysis system and simultaneous force measurements were captured at the forearm and thumb. Maintaining a near constant rate of pull, each trial required approximately 4–5 s. For each of the three trials, the IP joint was manually returned to full extension before initiating the next trial. Using load cell measurements at the thumb, we identified the IP angles at which the lower (1.3 N) and upper (7 N) thresholds were crossed.

FPL tendon excursion

Prior to attaching the load cell at the distal phalanx, tendon excursion was measured using a digital caliper for IP flexion 0°–30°

and 0°–60° for each wrist position (30° flexion, neutral, 30° extension, 20° radial deviation, 40° ulnar deviation). Measurements were made while in CMC 30° abduction and repeated at 40° abduction. To facilitate tendon excursion specifically within zone T2, the MCP joint was fixed at 0° throughout the experiment.

Statistical analysis

For IP passive motion, peak force across the FPL tendon in zone T2 was analyzed by two-factor ANOVA for each combination of wrist and CMC positions. Since CMC position was found to be significant in this full model ($p = 0.0164$), one-way ANOVA were performed across wrist positions for CMC 30° abduction and CMC 40° abduction. Lastly, post-hoc tests with Bonferroni adjustment were performed for all pairwise comparisons. For synergistic arcs of motion, one-way ANOVA was used to compare peak zone T2 forces for both the flexion/extension arc and radial/ulnar deviation arc at CMC positions 30° and 40°. In the case of induced IP active motion, one-way ANOVA was performed for the IP angle at which the measured force crossed the lower threshold of the SEZ (1.3 N). (Specimen 3 was excluded from IP active motion analysis because measured forces fell below the 1.3 N threshold). As in the passive motion analysis, post-hoc tests with Bonferroni adjustment were also performed for induced active motion. Analysis of excursion data included IP flexion from 0° to 30° while in wrist positions 1 (neutral) and 2 (30° extension). Specimen-specific mean values from three replicate FPL excursion (mm) measurements were used for analysis. A multivariable linear model of the specimen-specific mean excursion was then developed using CMC angle (fixed at 30° or 40°), wrist positions (fixed at neutral and 30° extension), and IP angle (treated as a continuous variable from 0° to 60°). Statistical significance was set at $\alpha = 0.05$.

Results

IP passive motion

A typical example of recorded forces generated across the tendon during passive IP flexion/extension is shown in Fig. 4. Results of ANOVA showed significant differences in mean peak forces across the 6 wrist positions ($p < 0.0001$) as shown in Fig. 5A (CMC 30° abduction) and Fig. 5B (CMC 40° abduction). These differences were driven entirely by wrist position 60° extension ($p \leq 0.05$). As one might expect, passive IP motion while at this extreme wrist angle generated forces in excess of the strength of a typical tendon repair. As shown in Fig. 5A (CMC 30° abduction), all observed peak forces for wrist position 30° extension fell within the SEZ limits. Furthermore, the mean peak force of 2.87 N [95% confidence interval: 1.68,4.06] fell well within the SEZ, suggesting that passive isolated IP motion while in 30° wrist extension is a biomechanically favorable mobilization method. Forces for passive IP motion while in wrist flexion, neutral, radial deviation, and ulnar deviation bordered 1.3 N and thus may risk generating insufficient force to overcome passive resistance to tendon glide post repair. As shown in Fig. 5B, passive IP motion while in CMC 40° abduction produced safe and effective forces for wrist 30° extension, 20° radial deviation, and 40° ulnar deviation.

Synergistic wrist motion with IP joint unrestrained

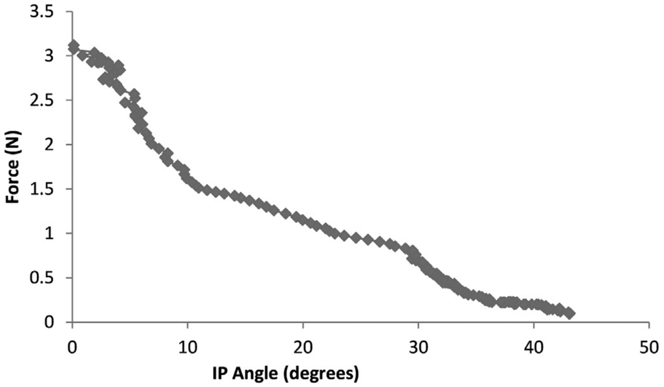

Fig. 4. Example of real-time zone T2 FPL forces recorded for passive motion from IP flexion (43°) to full extension (0°) with the wrist at 30° extension, CMC at 30° abduction and MCP blocked at 0°.

Although the synergistic motion results (Fig. 6) show that neither flexion/extension nor ulnar/radial deviation arcs of motion consistently generate sufficient peak force to overcome the lower limit of the SEZ (1.3 N, dashed line), it was interesting to observe that CMC position made essentially no difference during ulnar/radial deviation ($p = 0.8567$). However, CMC position did have a significant effect on the forces generated during flexion/extension motion, with a mean force of 0.302 N (SE = 0.035) at 30° abduction and a mean force of 1.12 N (SE = 0.122) at 40° abduction ($p = 0.0161$). As expected, force generated during the wrist extension phase consistently exceeded that measured during the flexion phase, and although tension levels were very low throughout the ulnar/radial deviation arc, radial deviation force tended to exceed that of ulnar deviation.

IP active motion

An example of recorded tendon force during induced active IP flexion is shown in Fig. 7. Fig. 8 illustrates the variation in IP angle at which the lower threshold of 1.3 N was crossed. ANOVA showed that the IP angle differed across the 7 useable specimens ($p = 0.0062$), but as shown in the figure, this was driven entirely by specimen 5 ($p < 0.05$). Over all specimens, 1.3 N was crossed at a mean IP angle of 33° [95% confidence interval: 2.7,3.8]. The between-specimen variance represented 57% of the total variance while the within-specimen variance (3 trials) was 43%. Across all specimens, only one reached the 7 N upper threshold limit (crossed at an estimated mean IP angle of 48°).

Tendon excursion

Because the above results from active and passive IP motion identified the wrist positions of neutral and 30° extension as biomechanically optimal, analysis of tendon excursion was focused on these two positions. Also, since CMC position (30° or 40° abduction) did not significantly influence tendon excursion ($p = 0.2345$), data were combined, resulting in 6 trials per specimen. Across all specimens, the estimated mean FPL excursion for IP flexion 0°–30° while in wrist neutral was 3.3 mm [95% confidence interval: 3.0,3.6] while that for wrist 30° extension was 3.8 mm [95% confidence interval: 3.4,4.1]. Fig. 9 shows that the relationship between mean excursion and IP angle was highly linear, with an estimated slope of 0.106 mm/degree. This indicates that every 10° of IP flexion will result in 1.06 mm of tendon excursion. Active range of motion results showed the lower threshold of 1.3 N was crossed at a mean IP angle of 33° in wrist neutral. From the relationship shown in Fig. 9, this would correspond to an FPL excursion of 3.6 mm.

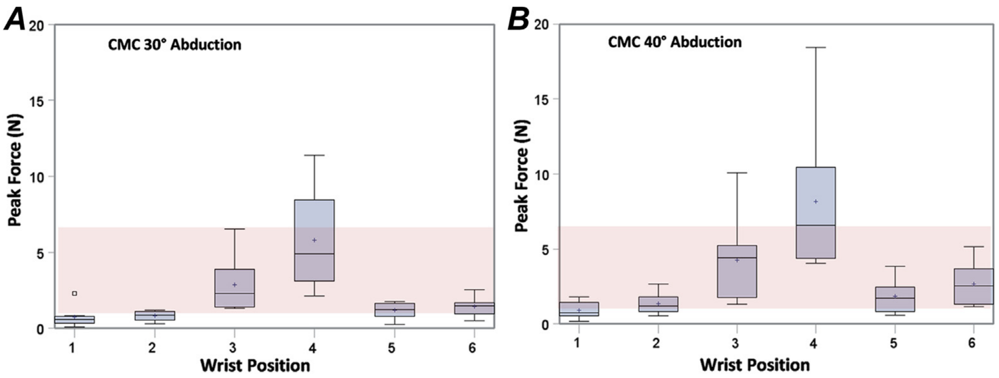

Fig. 5. Box-and-whisker plots showing estimated mean (plus sign), median (line), interquartile range (box) and range of peak forces across 8 specimens when performing IP passive motion for all wrist positions (1 = flexion 30°, 2 = neutral, 3 = extension 30°, 4 = extension 60°, 5 = radial deviation 20° and 6 = ulnar deviation 40°). A) CMC at 30° abduction; B) CMC at 40° abduction. The safe and effective zone (SEZ) of forces between 1.3 N and 7 N is highlighted.

Discussion

The goal of our experiments was to identify the SEZ for early post-surgical mobilization of the FPL tendon. We measured forces for passive, synergistic, and simulated active motions in various wrist and thumb positions, and compared them to the previously documented SEZ boundaries of 1.3 N–7 N. We also measured FPL tendon excursion distance while performing passive IP motion.

As shown in Fig. 5, passive flexion of the IP joint while in the different wrist/CMC positions produced a wide range of forces. Referring to the highlighted range of SEZ forces, biomechanically optimal tension was observed for wrist position 3 (30° extension) with the CMC at 30° abduction, and wrist position 6 (40° ulnar deviation) with the CMC at 40° abduction. However, because it is difficult to maintain a posture of 40° wrist ulnar deviation with CMC 40° abduction while passively moving the IP joint, this exercise could be challenging for the patient to perform. Furthermore, as expected, the highest force was measured in full IP extension (angle = 0°) and quickly decreased with joint flexion (Fig. 4). This reinforces the need to achieve full IP extension when performing passive-motion exercise. It is important to note, however, that IP hyper-extension was not measured and is not advised. Based on these results, in order to assure adequate force and tendon excursion, we recommend passively moving the thumb IP joint from 0° extension to the available flexion angle and back to full extension while maintaining a posture of wrist 30° extension, CMC 30° radial abduction and with the MCP blocked at 0°. To enhance successful exercise performance, a thumb-based exercise orthosis could be worn to block the MCP joint in neutral.

Synergistic wrist motion (wrist flexion with digit extension and wrist extension with digit flexion) is often advocated following finger-flexor repair.[19,20,36] While no synergistic protocol has previously been reported following FPL repair, we found that synergistic forces were typically too low to overcome minimum glide resistance. Furthermore, none of the trials approached the unsafe threshold of 7 N, suggesting that gentle active short-arc wrist motion will not put the repair at risk as long as the CMC, MCP and IP joints are in an unrestrained and relaxed state.

Fig. 8 shows the range of IP angles at which induced active motion produced a force of 1.3 N. Over all specimens, the estimated mean IP flexion angle that produced this force was 33° (95% confidence interval: 2.7,3.8). We therefore recommend that the patient be instructed to slowly perform gentle active flexion of the IP joint to approximately 35°–40° while blocking the three proximal joints in anatomic neutral (wrist 0°, CMC 30° abduction, and MCP 0°). During the first 3–5 days to 4 weeks post-surgery, before tendon healing has increased the breaking strength of the repair, this exercise should effectively move the tendon without risk of suture failure or gap formation.

Finally, having determined that the set of conditions given by wrist neutral, CMC 30° abduction and MCP 0° was biomechanically optimal for active IP motion, we were interested in determining whether the tendon moved the 2 mm distance which has been typically used as a guide to minimize adhesion formation. The linear mean trend shown in Fig. 9 indicates that FPL tendon excursion should increase 1.1 mm for every 10° of isolated IP flexion. This finding is similar to Brown and McGrouther's observation that FPL excursion was 1.3 mm for every 10° of IP motion.[17]

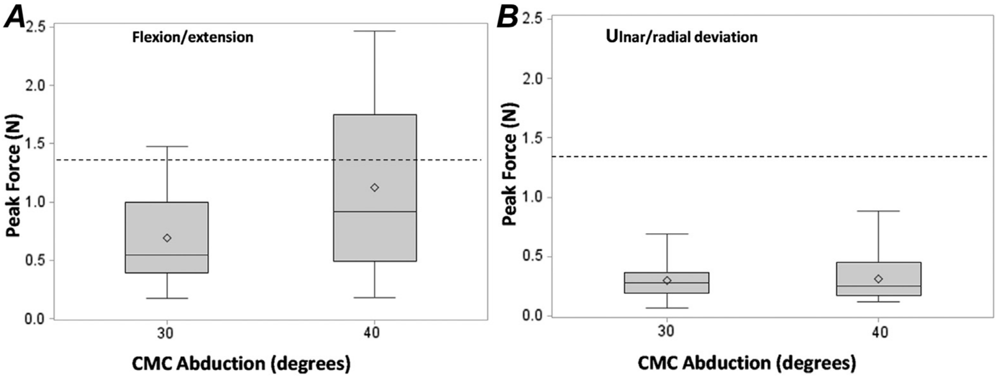

Fig. 6. Box-and-whisker plots showing estimated mean (diamond), median (line), interquartile range (box) and range of peak forces (N) for synergistic arc of wrist motion. Dashed line represents the lower threshold of SEZ (1.3 N). A) Flexion/extension arc of motion; B) Ulnar/radial deviation arc of motion.

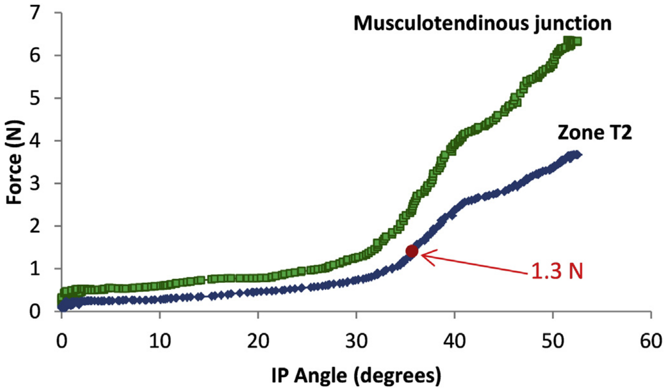

Fig. 7. Example of recorded tendon forces as the IP flexed in response to gentle graduated force applied at the musculotendinous junction. For this trial, the 1.3 N threshold in zone T2 was crossed at a measured IP flexion angle of 36° (red dot). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Using the lower 95% prediction limits shown in Fig. 9 as a guide, we conclude that essentially all patients would achieve 2 mm of excursion when the IP angle is flexed to 40° while in wrist neutral. Our direct measurements of passive IP flexion from 0° to 30° with the wrist in either neutral or 30° extension produced mean excursions of 3.3 mm and 3.8 mm, respectively.

The findings of this study differ somewhat from current clinical practice. Through controlled mechanical stress, our early-phase treatment emphasizes generating glide at the site of a four-strand repair in zone T2. To accomplish glide, our results suggest that the wrist be held in 30° extension during passive IP motion and that the IP joint be isolated during both passive and active exercise. Groth[37] reports that current practice generally follows a more conservative approach, where the wrist is held in flexion (although some authors have advocated a more neutral wrist[16,38,39]), and active thumb flexion is delayed until three weeks post-surgery. Although others have begun active thumb flexion during the first week, these authors did not recommend isolated IP joint exercises.[5] Even though a 7N-suture-gap-strength (the upper bound of our SEZ) is relatively low compared to other studies of surgical techniques,[40–42] lower-stress protocols may be more suitable for patients with impaired healing due to comorbidities or when tendons are repaired under tension.

The primary limitation of this study is the use of a cadaver model and the associated loss of physiologic effects such as muscle contraction and antagonist muscle tone. Likewise, our cadaver model did not replicate clinical forces produced across a repaired tendon. However, we accounted for gliding resistance of a repaired FPL tendon by setting a value for the lower limit of the SEZ as described by Kutsumi et al[31] and Buonocore et al.[32] Lastly, although care was taken to maintain tendon tension when attaching the load transducer to the thumb, the anatomy was unavoidably altered.

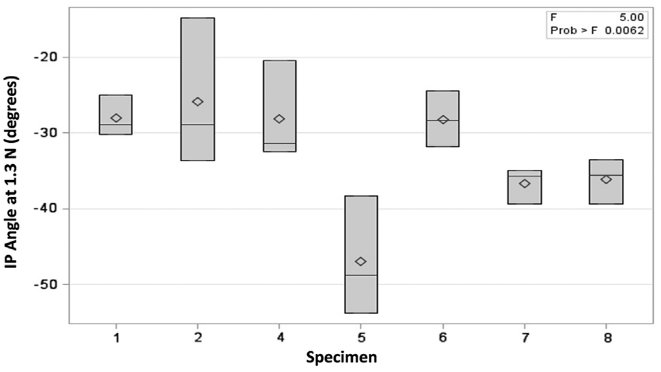

Fig. 8. Box plot of estimated mean (diamond), median (line), and interquartile range of IP angles (box) at which each specimen crossed the lower SEZ threshold of 1.3 N during induced active IP motion.

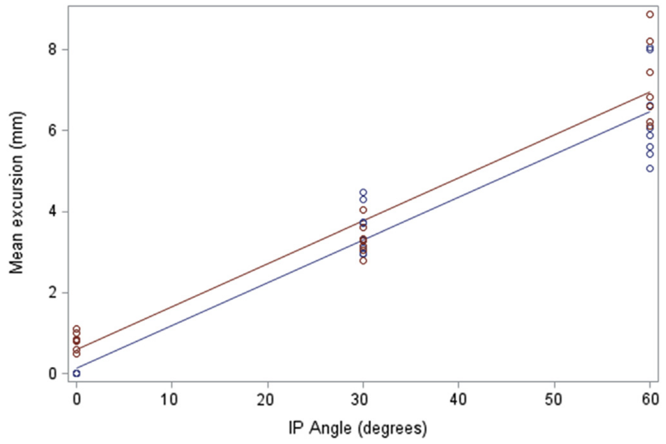

Fig. 9. Regression of specimen-specific mean values on the IP angle for 8 specimens with wrist neutral (blue) and wrist 30° extension (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Conclusions

Although early phase rehabilitation following zone T2 FPL repair has been recognized as "… more difficult than that at the same level in the fingers …",[43] studies specifically focused on measuring FPL mobilization forces have not previously been reported. Since Brown and McGrouther[17] showed that isolated IP motion was important to FPL glide, we were interested in whether isolated movement was safe and effective. We have extended their work here, by experimentally demonstrating that isolated IP motion can be performed safely and that the tenodesis effect of wrist extension is critical to effective passive IP motion. Likewise, we have shown that simulated active IP motion also produced forces within the SEZ. Whereas active motion has been advocated following surgical repair of finger and thumb flexors,[44–47] forces and mobilization parameters had not been verified previously for the thumb. Results from this biomechanical study suggest that actively flexing an isolated IP joint 35°–40° while maintaining a neutral position of wrist 0°, CMC 30° abduction, and MCP 0°, will safely and effectively move the FPL tendon at least 2 mm in zone T2. A treatment plan that incorporates our findings is outlined in the Appendix. In addition, we recommend clinical outcome studies to validate our recommended passive and active methods for early-phase FPL mobilization.

Acknowledgment

Grateful acknowledgement to Dr. Chunfeng Zhao for helpful discussions regarding experimental design.

References

1. Strickland JW. The scientific basis for advances in flexor tendon surgery. *J Hand Ther.* 2005;18:94–110. quiz 111.
2. Doyle JR, Blythe WF. Anatomy of the flexor tendon sheath and pulleys of the thumb. *J Hand Surg Am.* 1977;2:149–151.

3. Goehler CM, Murray WM. The sensitivity of endpoint forces produced by the extrinsic muscles of the thumb to posture. *J Biomech*. 2010;43:1553–1559.
4. Rack PM, Ross HF. The tendon of flexor pollicis longus: its effects on the muscular control of force and position at the human thumb. *J Physiol*. 1984;351:99–110.
5. Elliot D, Southgate CM. New concepts in managing the long tendons of the thumb after primary repair. *J Hand Ther*. 2005;18:141–156.
6. Howell JW, Peck F. Rehabilitation of flexor and extensor tendon injuries in the hand: current updates. *Injury*. 2013;44:397–402.
7. Noonan KJ, Blair WF. Long-term follow-up of primary flexor pollicis longus tenorrhaphies. *J Hand Surg Am*. 1991;16:653–662.
8. Kilbreath SL, Gandevia SC. Neural and biomechanical specializations of human thumb muscles revealed by matching weights and grasping objects. *J Physiol*. 1993;472:537–556.
9. Li ZM, Tang J, Chakan M, Kaz R. Complex, multidimensional thumb movements generated by individual extrinsic muscles. *J Orthop Res*. 2008;26:1289–1295.
10. Ouellette E, Makowski A. Fractures and joint injuries of the thumb. In: Berger RA, Weiss A, eds. *Hand Surgery*. Philadelphia: Lippincott Williams & Wilkins; 2004:194–230.
11. Amadio PC, Hunter JM, Jaeger SH, Wehbe MA, Schneider LH. The effect of vincular injury on the results of flexor tendon surgery in zone 2. *J Hand Surg Am*. 1985;10:626–632.
12. Kasashima T, Kato H, Minami A. Factors influencing prognosis after direct repair of the flexor pollicis longus tendon: multivariate regression model analysis. *Hand Surg*. 2002;7:171–176.
13. Wang JH, Guo Q, Li B. Tendon biomechanics and mechanobiology—a minireview of basic concepts and recent advancements. *J Hand Ther*. 2012;25:133–140. quiz 141.
14. Khanna A, Friel M, Gougoulias N, Longo UG, Maffulli N. Prevention of adhesions in surgery of the flexor tendons of the hand: what is the evidence? *Br Med Bull*. 2009;90:85–109.
15. Sirotakova M, Elliot D. Early active mobilization of primary repairs of the flexor pollicis longus tendon. *J Hand Surg Br*. 1999;24:647–653.
16. Sirotakova M, Elliot D. Early active mobilization of primary repairs of the flexor pollicis longus tendon with two Kessler two-strand core sutures and a strengthened circumferential suture. *J Hand Surg Br*. 2004;29:531–535.
17. Brown CP, McGrouther DA. The excursion of the tendon of flexor pollicis longus and its relation to dynamic splintage. *J Hand Surg Am*. 1984;9:787–791.
18. Lieber RL, Amiel D, Kaufman KR, Whitney J, Gelberman RH. Relationship between joint motion and flexor tendon force in the canine forelimb. *J Hand Surg Am*. 1996;21A:957–962.
19. Boyer MI, von der Heyde R. Flexor tendon injury. In: *Green's Operative Hand Surgery*. 5th ed. Philadelphia: Elsevier Churchill Livingstone; 2005.
20. Cooney W, Lin GT, An KN. Improved tendon excursion following flexor tendon repair. *J Hand Ther*. 1989;2:102–106.
21. Lieber RL, Silva MJ, Amiel D, Gelberman RH. Wrist and digital joint motion produce unique flexor tendon force and excursion in the canine forelimb. *J Biomech*. 1999;32:175–181.
22. Tanaka T, Amadio PC, Zhao C, Zobitz ME, An KN. Flexor digitorum profundus tendon tension during finger manipulation. *J Hand Ther*. 2005;18:330–338. quiz 338.
23. Zhao C, Amadio PC, Momose T, Couvreur P, Zobitz ME, An KN. Effect of synergistic wrist motion on adhesion formation after repair of partial flexor digitorum profundus tendon lacerations in a canine model in vivo. *J Bone Joint Surg Am*. 2002;84-A:78–84.
24. Zhao C, Amadio PC, Zobitz ME, Momose T, Couvreur P, An KN. Effect of synergistic motion on flexor digitorum profundus tendon excursion. *Clin Orthop Relat Res*. 2002:223–230.
25. Amadio P. The influence of biomechanical research on the management of flexor tendon injury. *J Hand Surg Br*. 2005;30:100–116.
26. Tanaka T, Amadio PC, Zhao C, Zobitz ME, Yang C, An KN. Gliding characteristics and gap formation for locking and grasping tendon repairs: a biomechanical study in a human cadaver model. *J Hand Surg Am*. 2004;29:6–14.
27. Kursa K, Lattanza L, Diao E, Rempel D. In vivo flexor tendon forces increase with finger and wrist flexion during active finger flexion and extension. *J Orthop Res*. 2006;24:763–769.
28. Zhao C, Amadio P, An K. Tendon friction, lubrication, and biomechanics of motion. In: Tang J, Amadio P, Guimberteau J, Chang J, eds. *Tendon Surgery of the Hand*. Philadelphia: Saunders; 2012:24–34.
29. Zhao C, Amadio PC, Tanaka T, et al. Effect of gap size on gliding resistance after flexor tendon repair. *J Bone Joint Surg Am*. 2004;86-A:2482–2488.
30. Amadio PC. Friction of the gliding surface. Implications for tendon surgery and rehabilitation. *J Hand Ther*. 2005;18:112–119.
31. Kutsumi K, Amadio PC, Zhao C, Zobitz ME, An KN. Gliding resistance of the flexor pollicis longus tendon after repair: does partial excision of the oblique pulley affect gliding resistance? *Plast Reconstr Surg*. 2006;118:1423–1428. discussion 1429–1430.
32. Buonocore S, Sawh-Martinez R, Emerson JW, Mohan P, Dymarczyk M, Thomson JG. The effects of edema and self-adherent wrap on the work of flexion in a cadaveric hand. *J Hand Surg Am*. 2012;37:1349–1355.
33. Gelberman RH, Boyer MI, Brodt MD, Winters SC, Silva MJ. The effect of gap formation at the repair site on the strength and excursion of intrasynovial flexor tendons. An experimental study on the early stages of tendon-healing in dogs. *J Bone Joint Surg Am*. 1999;81:975–982.
34. Silva MJ, Boyer MI, Gelberman RH. Recent progress in flexor tendon healing. *J Orthop Sci*. 2002;7:508–514.
35. Silva MJ, Brodt MD, Boyer MI, et al. Effects of increased in vivo excursion on digital range of motion and tendon strength following flexor tendon repair. *J Orthop Res*. 1999;17:777–783.
36. Strickland JW. Development of flexor tendon surgery: twenty-five years of progress. *J Hand Surg Am*. 2000;25:214–235.
37. Groth GN. Current practice patterns of flexor tendon rehabilitation. *J Hand Ther*. 2005;18:169–174.
38. Kitsis CK, Wade PJF, Krikler SJ, Parsons NK, Nicholls LK. Controlled active motion following primary flexor tendon repair: a prospective study over 9 years. *J Hand Surg Br*. 1998;23B:344–349.
39. Sandow MJ, McMahon M. Active mobilisation following single cross grasp four-strand flexor tenorrhaphy (Adelaide repair). *J Hand Surg Eur Vol*. 2011;36E:467–475.
40. Angeles JG, Heminger H, Mass DP. Comparative biomechanical performances of 4-strand core suture repairs for zone II flexor tendon lacerations. *J Hand Surg Am*. 2002;27:508–517.
41. Barrie KA, Wolfe SW, Shean C, Shenbagamurthi D, Slade 3rd JF, Panjabi MM. A biomechanical comparison of multistrand flexor tendon repairs using an in situ testing model. *J Hand Surg Am*. 2000;25:499–506.
42. Choueka J, Heminger H, Mass DP. Cyclical testing of zone II flexor tendon repairs. *J Hand Surg Am*. 2000;25:1127–1134.
43. Evans RB. Managing the injured tendon: current concepts. *J Hand Ther*. 2012;25:173–189. quiz 190.
44. Braga-Silva J, Kuyven CR. Early active mobilization after flexor tendon repairs in zone two. *Chir Main*. 2005;24:165–168.
45. Evans RB. Zone I flexor tendon rehabilitation with limited extension and active flexion. *J Hand Ther*. 2005;18:128–140.
46. Groth GN. Pyramid of progressive force exercises to the injured flexor tendon. *J Hand Ther*. 2004;17:31–42.
47. Starr HM, Snoddy M, Hammond KE, Seiler 3rd JG. Flexor tendon repair rehabilitation protocols: a systematic review. *J Hand Surg Am*. 2013;38:1712–1717. e1711–1714.

Appendix

Early-phase treatment plan following four-strand repair of zone T2 flexor pollicis longus.

3–5 days to 4 weeks post-surgery.

- Remove bulky dressings that may impede motion or interfere with orthosis fit. Apply finger sock to thumb and thin elastic bandage to hand and forearm.
- Fabricate a forearm-based dorsal blocking orthotic device:
    - Wrist neutral (0° flexion/extension/ulnar deviation/radial deviation)
    - Thumb CMC neutral (0° flexion/extension, 30° radial abduction)
    - Thumb MCP neutral (0° flexion/extension)
    - Thumb IP neutral (0° flexion/extension)

Note: Suggest including index finger to prevent inadvertent thumb/index pinching and also to address possibility of an anomalous slip between FPL and index flexor digitorum profundus.

- Gentle warm-up exercises
    - In wrist neutral, rest ulnar side of forearm and hand on table. Perform slow and gentle passive motion first at the IP and then at the MCP. To isolate the IP, a thumb-based exercise orthosis may be worn to block the CMC and MCP. Perform 10 repetitions for each joint followed by 10 repetitions of passively moving IP, MCP, CMC simultaneously.
- Passive tendon mobilization exercise
    - With ulnar side of forearm and hand on table, gently extend the wrist 30°. Placing hand and forearm on a piece of paper with a straight line drawn for the forearm and a second line at a 30° angle for the hand, may guide safe wrist positioning.
    - While in wrist 30° extension and CMC/MCP neutral, perform passive IP motion. To facilitate isolating the IP, a thumb-based exercise orthosis may be worn to block the CMC and MCP. It is important to return to full IP extension, but at no time should the IP joint be taken into hyper-extension. Perform 10 repetitions.
- Active mobilization exercise
    - While in wrist neutral, block the CMC and MCP with an exercise orthosis or the other hand and have patient slowly perform gentle active IP flexion 35–40°. Perform 10 repetitions.

Perform program once every 1–2 h for a total of 5–8 times per day. Orthosis is to be worn except while exercising.

JHT Read for Credit

Quiz: #383

Record your answers on the Return Answer Form found on the tear-out coupon at the back of this issue or to complete online and use a credit card, go to *JHTReadforCredit.com*. There is only one best answer for each question.

#1. The evidence presented may best be described as
   a. absolute
   b. equivocal
   c. redundant
   d. theoretical

#2. The information would best be applied
   a. in a research laboratory setting
   b. following a Zone II FDP rupture
   c. in clinical management following repair of a FPL laceration
   d. in a pediatric population

#3. Tensile forces were measured in a
   a. series of human cadaveric specimens
   b. single canine cadaver
   c. series of human patients at the Mayo Clinic
   d. series of patients from multiple clinics throughout the US and Canada

#4. Motion was directed at the
   a. isolated MP joint
   b. isolated IP joint
   c. MP and IP joints
   d. radiocarpal joint

#5. Wrist and thumb motions were identified for safe and effective early mobilization
   a. false
   b. true

When submitting to the HTCC for re-certification, please batch your JHT RFC certificates in groups of 3 or more to get full credit.