Zone I Flexor Tendon Rehabilitation with Limited Extension and Active Flexion

Roslyn B. Evans, OTR/L, CHT
Indian River Hand and Upper Extremity Rehabilitation
Vero Beach, Florida

ABSTRACT: This article describes an immediate active motion protocol for primary repair of zone I flexor tendons treated with tendon to tendon, or tendon to bone repair, and reviews clinical results. A rehabilitation protocol is proposed that will limit excursion of the zone I repair by blocking full distal interphalangeal (DIP) extension and by applying controlled active tension to both the unrepaiured flexor digitorum superficialis (FDS) and the repaired flexor digitorum profundus (FDP). The rehabilitation technique utilized a dorsal protective splint with a relaxed position of immobilization with 30 degrees of wrist flexion, 40 degrees of metacarpophalangeal (MCP) joint flexion, and a neutral position for the proximal interphalangeal (PIP) joints without dynamic traction. In addition, within the confines of the dorsal splint, the involved DIP joint was splinted at 40-45 degrees to prevent DIP joint extension during the early wound healing phases. Relaxed composite flexion was used to apply active tension to both the uninjured FDS, and the repaired FDP. This technique applies excursion of approximately 3mm to the zone I tendon in a limited arc (45-75 degrees). The modified position of active flexion applies low loads of force (< 500 g), even with drag considered. This technique is supported by previous mathematical studies of excursion and internal tendon force, and clinical experience. Forty nine cases treated over a 10-year period were reviewed, and eight were excluded for incomplete follow-up. The use of this protocol for 41 zone I flexor digitorum profundus repairs by 12 different surgeons using varied surgical techniques was evaluated. None of the tendon to tendon repairs used more than two suture strands for the core repairs. Mean total active range of motion was 142 degrees (PIP 95 degrees plus DIP 47 degrees), or 81% of normal. Three tendons ruptured in non-protocol-related incidents and were excluded from the study. Results from this clinical study support the use of limited DIP extension combined with active tension with conventional repair in zone I.


HISTORICAL PERSPECTIVE

Historically, the management of zone I flexor tendon repairs have followed similar patterns of rehabilitation protocols as zone II flexor repairs. Those techniques have included immobilization, passive motion, and, in the last two decades, active motion protocols. Extensive bibliographies are available that define the progression of postoperative management methods and the scientific rationale for those changes. Recent advances in repair techniques at this level have been designed to tolerate the forces of active tension, and some have questioned the ability of tendon-to-bone repairs to tolerate any active motion protocols. While zone I injuries have been recently studied in terms of repair technique and healing properties, there is still little detailed information on their optimum postoperative management, other than recommendations for passive or
active exercise regimens that mobilize repairs in both zones I and II with similar protocols.1–4

In addition, functional results following zone I repair have been poorly documented in the literature, and methods of evaluation have been questioned.17,18 Results of zone I injuries are often combined with those in zone II injuries, given liberal allowances for "good" or "excellent" categories, and, with a few exceptions19,18,19 do not report DIP motion separately. While some studies report a high percentage of "good" and "excellent" results, and others minimize the importance of distal joint flexion,20,21 it is my experience that a significant number of these injuries return function that is not satisfactory to the patient. Most patients are not satisfied unless the proximal interphalangeal (PIP) and DIP joints are free of contracture, the PIP joint flexes independently, and the distal joint flexes to at least 40 degrees at the end arc of flexion.1 What may be termed satisfactory by the surgeon or therapist is often not satisfactory to the patient. Reports on patient satisfaction regarding return of terminal flexion, grip strength, or coordination associated with this injury are also limited. A recent review produced only two studies that defined outcomes with regard to patients' self-evaluation.9,10

Description and Functional Significance

The zone I finger flexion mechanism is the FDP. This zone extends from the terminal portion of the FDS insertion to the FDP insertion.22,23 The A4, C3, and A5 pulleys are found in the digit in zone I; of these the A4 has the greatest functional significance (Figure 1).5,24,25 While the A4 pulley may be considered to be a part of zone II by some, it contains only a single tendon. It functions to maintain the appropriate moment arm for the zone I profundus and it is more likely to be a source of pathology in the zone I injury than in zone II.

The significance of the FDP has been defined by a number of investigators. The profundus tendon is the only flexor of the DIP joint, and it also influences the PIP joint in that it has the greatest moment arm acting on the PIP joint.26 The predominance of activity of the FDP over the FDS in most digital motions has been demonstrated electromyographically.27 The FDP is the major flexor of the finger during synchronous composite flexion of all digital joints, whereas the FDS contributes more to power grip and is essential for finger flexion when the wrist is flexed.26–29 Loss of distal joint flexion of the index or long finger compromises pinch and grip function30,31 and poses limitation to the skilled musician or craftsman. The limited action of the FDS in the small finger, and its incidence of congenital absence increases the importance of the FDP to ulnar grip.32 Loss of FDP function in the small finger presents a serious functional problem because in most cases the FDS does not provide adequate power and function for the digit.32–34

Natural Progression of the Zone I Flexor Injury

Zone I flexor tendon injuries may present as closed avulsion injuries, often with a large fragment of bone, or typically as lacerations of the last centimeter of the FDP or under the A4 pulley.30,35,36 Lacerations may
involve the pulley system and volar plate of the distal joint and tendon.\textsuperscript{30}

Surgical treatments are well described in the literature as open reduction and internal fixation of the fracture fragment that reestablishes the tendon insertion; tendon to bone repair for true avulsion injuries or when the fracture fragment is small; tendon advancement; and tendon to tendon repair.\textsuperscript{36} Research continues in an effort to strengthen repair at this level to allow immediate active motion for the zone I repair.\textsuperscript{11}

Closed profundus injuries are often misdiagnosed, leading to delayed treatment and the need for secondary or salvage procedures that may compromise results. An unrepaired FDP results in loss of DIP flexion, possible hyperextension of the DIP joint, impaired pinch, and loss of grip strength.\textsuperscript{30,31,33} The retracted proximal stump of the FDP may act as a mechanical block to the FDS, thus preventing PIP flexion beyond 90 degrees.\textsuperscript{30} The FDP that retracts into the palm may produce pain or tenderness in the palm, which can limit grip ability.\textsuperscript{33} A dynamic deformity termed the "lumbrical plus" finger may result because profundus retraction causes proximal migration of the lumbrical origin. Lumbrical tension is increased, and attempts at digital flexion may result in extension.\textsuperscript{37} Hypertrophic synovitis can occur within the flexor sheath with an untreated profundus avulsion secondary to hemorrhage due to ruptured vinculae from tendon retraction and torn paratenon.\textsuperscript{35} Scar may form that will interfere with FDS excursion and may contribute to PIP flexion contracture.

Repairs under excessive tension following tendon advancement or grafting of any of the ulnar three profund, (by virtue of their interdependence) can result in a quadriga syndrome limiting digital flexion of the adjacent uninjured digits.\textsuperscript{38,39} Resection of the A4 pulley will limit DIP flexion, allow bowstringing of the FDP and contribute to DIP joint flexion contracture (Burkhalter WE. Personal communication, June 1989).\textsuperscript{34}

Gap formation at this level may be especially significant because the zone I tendon has a small moment arm, limited excursion, and less tensile strength owing to the smaller diameter of the repaired tendon. This may explain a propensity to gap with rehabilitation protocols that allow full extension at the PIP and DIP joints simultaneously within protective dorsal splints. In addition, experimental studies have demonstrated that there is no increase in the ultimate strength of tendon-to-bone repairs in terms of healing during the first 6 weeks after repair with either a four- or eight-strand suture.\textsuperscript{7} A well-defined area of hypovascularity has been identified in a study of 36 cadaver digits subadjacent to the volar plate of the DIP joint,\textsuperscript{16} which may have relevance to tendon healing at this level. These studies may further support the limited distal joint extension concept for post-FDP-repair management.

In summary, zone I is a unique region that differs considerably in mechanics, kinematics, and function from zone II. At this level, the flexor system is a one-tendon system with a small moment arm and limited excursion. It deserves to be treated differently from the more proximal zones. A rehabilitation protocol is proposed that will limit excursion of the zone I repair by blocking full DIP extension and applying controlled active tension to both the unrepaird FDS and repaired FDP.

Clinical Application: Limited Extension, Active Flexion in Zone I

Repaired tendons in zone I are treated with a combination of the limited zone I protocol\textsuperscript{1} and immediate active short arc motion (SAM) previously described for zones I and II with conventional repair.\textsuperscript{40} The LEAF program is appropriate for the zone I profundus injury repaired primarily with end-to-end repair, advancement, or reinsertion into bone. Therapy is initiated within 24–48 hours postoperatively with wound care, edema control, splinting, and the described exercise. The focus of the first treatment session is patient education, edema control (the involved digit should be dressed lightly and wrapped in a single layer of Coban [3M Medical Surgical Division, St. Paul, MN]), and setting up the proper splint geometry.

The repairs are protected with a dorsal static splint which positions the wrist at 30–40 degrees flexion, the metacarpophalangeal (MP) joints at 30 degrees flexion, and the PIP joints at 0 degrees, with dorsal protection extending to the fingertips (Figure 2). The affected DIP joint is splinted at 40–45 degrees flexion with a second dorsal digital splint that extends from the proximal portion of the middle phalanx (P\textsubscript{2}) to the tip distal phalanx (P\textsubscript{3}) (Figure 2). The digital splint is taped only at the middle phalanx with 1-inch Transpore tape (3M Medical Surgical Division). Dynamic traction is not employed.

The patient is instructed to perform the following exercise regimen within the confines of the two splints with frequent repetitions throughout the day. The DIP joint is passively flexed from the 40–45 degrees flexion angle in the digital splint to 75 degrees (or full available flexion) (Figure 3A); the digits are passively placed in a composite fist position (Figure 3B), and then in a modified hook fist position (Figure 3C), which is made possible by the position of modest MP joint flexion within the protective dorsal splint. The MP joints are passively flexed by the uninvolved hand, and the patient actively extends the PIP joint to full extension, with manual pressure from the contralateral hand holding the P\textsubscript{1} in full flexion (Figure 3D). The unaffected fingers are posi-
tioned in extension while a gentle "place and hold" active exercise for the FDS in the injured digit is performed (Figure 3E).

During structured therapy sessions, these same exercises are repeated; in addition, under therapist supervision, the hand is removed from the splint for wound care, wrist tenodesis (Figures 4A and 4B), and the active exercise component of the SAM protocol (Figure 5).

Gentle passive flexion exercises should precede the active hold exercise to reduce the resistance of edema and tight joint. Slow, repetitive, passive motions are applied to the digits until passive torque at the end arc of flexion is less than 300 g force (the therapist can learn to appreciate the feel of the resistance to passive motion by working with the Haldex pinch meter [JLL Tools; J.D. Mard Industries, Tuckahoe, NY]). The therapist then positions the patient's wrist in 20 degrees of extension, the MP joints at 75–80 degrees flexion, the PIP joints at 70–75 degrees flexion, and the DIP joints at 40 degrees flexion (the position of SAM). The patient is asked to gently maintain this position to create active tension in the flexor system.

To control the amount of external load applied to the fingertip (and thus the internal tension transmitted to the repair site) a small (<150 g) calibrated Haldex pinch meter (JLL Tools) is used to measure the force of flexion. The technique for measuring external load is as follows: a string is applied to the gauge arm of the pinch meter at a 90-degree angle and also around the mid-section of the distal phalanx (P3) at a 90-degree angle. In the position of SAM previously described, the patient is asked to apply 15–20 g force at the fingertip (Figure 5). This should first be demonstrated to the patient on an uninjured digit to help him or her appreciate how gentle and controlled the forces of active motion should be, and then during the active hold component for the injured digit, that force should be observed as measured on the Haldex pinch meter by both patient and therapist. Once the patient appreciates the force required for SAM measuring with the Haldex is not necessary.

These exercises are supplemented by a wrist tenodesis exercise in which the therapist passively holds the digits of the injured hand into a composite fist and simultaneously extends the wrist to approximately 30–40 degrees (Figure 4A). The wrist is then passively placed into approximately 60 degrees flexion while the digits are allowed to position in extension through a natural tenodesis action; the P2-P3 dorsal splint prevents simultaneous PIP and DIP extension (Figure 4B).

During the first three or four weeks of wound healing, the DIP joint is not allowed to extend beyond 40–45 degrees flexion, but the patient passively moves the joint to greater flexion and moves with controlled active tension under therapist supervision, and with a home program if the patient is deemed reliable. The distal joint splint is removed between 21 and 25 days, but no passive extension force is applied to the DIP joint until after week 4. The usual tendon gliding exercises, which are well described in the literature, are initiated by the patient between weeks 3 and 4. At this point the tensile strength of the repair is expected to increase, and greater angles of flexion are encouraged with the composite fist. The patient attempts active hold exercises with the digits to the palm, and a very gentle isolated distal joint flexion. Care should be taken not to place pressure against the repair site with firm blocking exercises as this may impede tendon glide and elevate tension at the repair site.

The dorsal wrist and digital splint is reheated and remolded at week 4 to place the wrist in a neutral position and to maintain the MP joints in slight flexion to place the hand in a more advantageous position for controlled active motion by the patient. Splint protection should continue until week 6 or 7 if tendon glide is satisfactory and adhesion minimal.

Clinical Experience

A total of 41 digits (out of 49) treated with the LEAF protocol were available for follow-up during a 12-week postoperative period. These cases were treated over a ten-year period, and referred by 12 different surgeons who used varying surgical techniques for tendon repair. Repairs with tendon to bone (13) and tendon to tendon (28) were treated with the same protocol by one therapist (RBE).
FIGURE 3. (A) The distal interphalangeal joint is flexed passively from the 40–45 degree flexion angle within the two protective splints to full flexion, theoretically providing some mechanical stress at the repair site without causing gap formation. (B) The digits are passively placed in the full fist position to provide passive excursion of the flexor digitorum profundus and flexor digitorum superficialis and to reduce drag in preparation of the active exercise. (Reprinted from Evans RB. A study of the zone I flexor tendon injury and implications for treatment. J Hand Ther. 1990;3:138, Fig. 9C, with permission.) (C) The digits are passively placed in a modified hook fist position made possible by the modest position of MP flexion to encourage differential excursion between the FDP and FDS. (Reprinted from Evans RB. A study of the zone I flexor tendon injury and implications for treatment. J Hand Ther. 1990;3:138, Fig. 9B, with permission). (C) The MP joints are passively hyperflexed by the uninvolved hand while the PIP joints are actively extended to absolute 0 degrees to prevent PIP joint flexion contracture. (Reprinted from Evans RB. A study of the zone I flexor tendon injury and implications for treatment. J Hand Ther. 1990;3:138, Fig. 10, with permission). (E) The unaffected digits are placed in extension while a gentle "place and hold" exercise for the FDS is performed. This position will decrease internal tendon tension in the flexor digitorum profundus while activating the unrepair FDS. (Reprinted from Evans RB. A study of the zone I flexor tendon injury and implications for treatment. J Hand Ther. 1990;3:138, Fig. 11, with permission).
All digits were evaluated with regard to functional outcome as determined by active interphalangeal (IP) motion. The results for each digit were calculated as a percentage of normal (excluding the MP joint) according to the following formula:

\[ \text{PIP+DIP flexion - extensor lag} \times 100 = \%	ext{ normal PIP+DIP flexion} \div 175 \text{ degrees} \]

Results were classified by the following suggested criteria: an excellent result was 85–100% normal motion (>150 degrees), good was 70–84% (125–149 degrees), fair was 50–69% (90–124 degrees), and a poor result was less than 50% (<90 degrees).

Forty-one digits treated with the SAM protocol in zone I had a mean total active motion (TAM) of 142 degrees, PIP flexion of 95 degrees, and DIP of 47 degrees. The average day that motion was initiated was day 3, average day of discharge day 52. The mean percentage of normal was 81%, or the high range of the good category. Three ruptures occurred in zone I and were excluded from the results, all with deviation from protocols (i.e., one lifting a heavy object, two when removing the protective splint prematurely). The results obtained in my practice with the LEAF protocol are modestly improved over my previously described zone I limited passive motion protocol by 12 degrees for TAM, and improved over my earlier results with standard passive protocols by 41 degrees. Appreciable differences between the types of repair were not noted. Tendon-to-bone repairs demonstrated no difference in flexion, but did show a greater extension deficit of 2 degrees and some mild skin and nail problems associated with the over-tie button and wires (Table 1).

**DISCUSSION**

This technique for controlled active tension and limited distal joint extension addresses problems associated with the zone I injury: repair site gapping, unsatisfactory distal joint flexion, PIP flexion contracture, and incomplete FDS glide. It revises and updates an original clinical research study to add active tension for the distal joint and to report continued clinical experience.

As with any early motion program, the therapist must consider the variables regarding the timing of stress application, tendon excursion and internal force application applied with splint geometry and

**FIGURE 4.** (A) The wrist and finger tenodesis exercise is performed under therapist supervision. The therapist passively holds all fingers of the injured hand into the palm and simultaneously extends the wrist to 30–40 degrees of extension. (Reprinted from Evans RB. A study of the zone I flexor tendon injury and implications for treatment. J Hand Ther. 1990;3:138, Fig. 12A, with permission). (B) The wrist is then passively flexed to full flexion while the fingers are allowed to position in extension through a natural tenodesis action. (Reprinted from Evans RB. A study of the zone I flexor tendon injury and implications for treatment. J Hand Ther. 1990;3:138, Fig. 12B, with permission).

**FIGURE 5.** External force is measured with the Haldex pinch meter as the patient applies 15–20 g force at the mid portion of the distal phalanx in the active hold position of SAM. (Reprinted from Evans RB, Thompson DE. The application of force to the healing tendon. J Hand Ther. 1993;6:276, Fig. 12B, with permission.)
TABLE 1. Comparison of Range of Motion between Limited Extension and Active Flexion (LEAF), Limited Zone I Technique, and Passive Motion Technique for Zone I Flexor Tendon Repairs

<table>
<thead>
<tr>
<th>Criteria Compared</th>
<th>LEAF</th>
<th>Limited Zone I</th>
<th>Passive Zone I</th>
</tr>
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<tr>
<td>Number of digits</td>
<td>41</td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>PIP flexion</td>
<td>95°</td>
<td>89°</td>
<td>76°</td>
</tr>
<tr>
<td>DIP flexion</td>
<td>47°</td>
<td>41°</td>
<td>25°</td>
</tr>
<tr>
<td>TAM</td>
<td>142°</td>
<td>130°</td>
<td>101°</td>
</tr>
<tr>
<td>% normal</td>
<td>81%</td>
<td>74%</td>
<td>58%</td>
</tr>
<tr>
<td>Category</td>
<td>Good+</td>
<td>Good-</td>
<td>Fair</td>
</tr>
</tbody>
</table>

controlled, exercise, and duration of exercise. The decision-making process is simplified by asking the questions why, when, how far, how much, and how often.

Why?

Early active motion as a technique for controlling adhesion and improving healing has support in numerous experimental and clinical studies. Many elegant studies have demonstrated the positive influence of stress on healing tendon with documented improvement of tensile strength, improved gliding properties, increased repair site DNA, and accelerated changes in peritendinous vessel density and configuration. Motion may enhance the diffusion of synovial fluid within the tendon in synovial regions and will increase fibronectin concentration and fibroblast chemotaxis at a tendon repair site. Stress-induced electrical potentials may increase tendon tissue healing potential. Biomechanically, the immobilized tendon loses tensile strength in the first two weeks after repair, and loses gliding function by the first ten days after repair.

The last two decades have produced active motion protocols that have improved functional results over the traditional passive regimens, and the application of some immediate active tension is becoming the standard of care in flexor tendon rehabilitation. A number of studies on excursion at this level support active over passive regimens. Experimentally, passive motion in flexor tendons has demonstrated to be as little as half that of theoretically predicted values under conditions of low tension. Actual tendon excursion will be equal to the predicted excursion of earlier studies only when more than 300 g tension is applied to the repair site. A component of active motion has been recommended for true tendon excursion at the A3 and A4 pulley levels because of poor excursions in these regions with passive motion. Significant improvements have been demonstrated with regard to tendon excursion at both the middle and proximal phalanx levels with active over passive regimens.

However, the ability of some zone I repairs to tolerate active motion has recently been questioned. 12, 13

When?

Experimental studies support the application of some stress by five postoperative days and have demonstrated improved tensile strength, healing efficiency, fibronectin concentration, fibroblast chemotaxis, and better orientation of fibroblasts. Delaying mobilization by three days decreases the work of flexion associated with postoperative edema and increases the safety margin with active tension. In a study of the ratio of resistance to tendon gliding and repair tensile strength the least favorable ratio was at seven days after repair whereas the most favorable ratio was at five days after repair. 1 Constrained digital motion started by five postoperative days allows progressive tendon healing without the intervening softening phase in experimental studies noted in earlier studies. In the LEAF program, patients are seen 24–48 hours postoperatively to initiate edema control with Coban wraps (3M Medical Surgical Division), proper splint positioning to prevent PIP flexion contracture, and for patient education. Motion is initiated as inflammation subsides by the third to fifth day to ensure that some true tendon excursion is effected before restricting adhesions are formed. Delaying clinical intervention by more than 5 days has been shown to have an adverse clinical effect on combined IP motion. My experience is that, in some cases, PIP joint contractures can become a problem as early as three to five postoperative days.

How Far?

Three or four millimeters of excursion for the repaired zone I FDP is suggested, with no restriction of excursion for the unrepairs FDS. In the original study, FDP excursions in zone I were calculated mathematically based on Brand’s radian concept and studies of tendon excursion measured at this level. It was determined that angular rotation of the DIP joint from 45 to 75 degrees would theoretically provide approximately 3 mm FDP excursion in the protected zone, and 40–80 degrees would provide approximately 3.5 mm excursion. (Figures 6A and 6B) This protected range of excursion would be compatible with that suggested by Duran and House 84 and later by Gelberman et al. to maintain functional tendon gliding. More recent experimental studies have demonstrated that 1.7 mm tendon excursion may be sufficient to prevent adhesion formation, but most investigators recommend more excursion in the clinical situation.

It has been demonstrated that distal joint motion is critical to maintaining differential gliding of the FDP
the greatest moment arm for the flexor tendons, produces the greatest tendon excursions with motion.\(^{103}\) The addition of a synergistic tendons and flexion and extension exercise\(^ {5,8,6,100-102}\) has been added to both passive and active postoperative regimens to further increase tendon excursion\(^ {102}\) and to decrease internal tendon forces at the repair site by positioning the wrist in neutral to slight extension for the "active hold" exercise component of active protocols.\(^ {40,62,63,104}\) Recent studies have demonstrated experimentally that wrist tenodesis combined with MP extension produces more effective FDP tendon excursion (Dr. Peter Amadio, personal communication; manuscript submitted to the Journal of Hand Therapy, 2005).

Splint geometry is designed to maximize tendon excursion in a safe zone. The dorsal hood splint is positioned with a relaxed wrist position of 20–30 degrees flexion to reduce the viscoelastic resistance of the antagonist extensors. The MP joints are positioned at 30 degrees flexion to relax the force of the lumbrical muscle on the profundus tendon,\(^ {26,29}\) to allow the digits to be placed passively into a modified hook fist position exercise to increase differential excursion of the FDP and FDS tendons,\(^ {42,43}\) and to allow a safer position for the active tension component of the exercise regimen. Dynamic traction is not used to prevent PIP flexion contracture.

The digital dorsal P\(_1\);P\(_2\) splint, which holds the DIP flexed at 45 degrees the first 21–28 days, is designed to prevent gap formation and to provide the controlled range for passive flexion from 45 to 75 degrees flexion within the confines of this splint. Maintaining DIP flexion may position the zone I tendon proximal to its normal resting length and allow adhesion to form about the tendon in a shortened position.\(^ {1}\) Regaining extension is a preferable rehabilitation challenge as compared to regaining DIP flexion with a scarred, elongated, or gapped repair site. This distal joint extension block also neutralizes the action of the oblique retinacular ligaments which act to extend the distal joint with a dynamic tenodesis action when the P\(_2\) (PIP joint) is extended by virtue of their attachment to the terminal extensor tendon (Dr. Paul Brand, personal communication, June 8, 1988).\(^ {29}\)

Flexion contracture at the distal joint will not be a problem unless the A4 pulley is resected (Burkhalter WE. Personal communication, June 1989).\(^ {24,26}\) It may be that the distal joint is not prone to flexion contracture with three or four weeks of positioning in flexion because the volar plate at this level has no clear attachment to bone, as it does at the PIP joint,\(^ {105-106}\) and because the capsular recess between the meniscal leaf of the volar plate and the volar articular facet is much less distinct at the DIP than at the PIP joint.\(^ {105,106}\) Flexion from 40 to 75 degrees serves to lubricate the joint and provide motion to the capsular structures as well as the zone I tendon.

and FDS.\(^ {85,86,97}\) Gelberman et al\(^ {75}\) have demonstrated that at least 35 degrees of DIP motion is necessary to effect 3–4 mm differential glide of the FDP on the FDS. Hook fist position provides the greatest differential excursion between the two tendons.\(^ {42,43}\)

Greater excursion is effected at the more proximal levels with exercise patterns and splint geometry. The FDS is allowed full excursion with the injured finger isolated and active hold of the PIP at 90 degrees flexion. Proximal interphalangeal joint motion is critical to FDP excursion\(^ {85,86,94,99}\) and to prevent PIP flexion contracture. The PIP is allowed full extension with the wrist, MP, and DIP held in flexion.

Wrist tenodesis further increases excursion of the FDS and proximal FDP.\(^ {86,100-102}\) The wrist joint, with

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Flexor tightness can be corrected with night digital extension splinting at five postoperative weeks.

How Much?

**Estimating Internal Tendon Forces**

Force application with tendon protocols should be controlled in a reliable and repeatable manner to reproduce internal tendon forces that are compatible with the tensile strength of the repair technique that is being stressed.

Several studies have measured in vivo tendon forces but both without controls for applied external force, and both on uninjured tendon. While this information is helpful, estimating internal tendon tension for rehabilitation programs requires more detailed information. Internal tendon forces in the digital flexor or extensor system are determined by (1) joint angles of the wrist and digital joints which alter the resistance of the antagonistic muscle-tendon units; (2) the applied external load; (3) the resistance of edema, hematoma, periarticular tissues, suture bulk, and bandaging; and (4) the speed of motion. These concepts are reviewed in detail elsewhere and are beyond the scope of this article.

Guidelines for loading a flexor tendon repair with a conventional suture, two-strand core with an epitendinous suture have been formulated based on mathematical modeling of internal forces as they relate to joint position and external load with drag eliminated. For the purpose of that study, the wrist was positioned at 45 degrees extension to reduce the resistance of the antagonistic extensors while the digital joints were positioned in (1) the relaxed position, (2) the position of immediate active SAM, and (3) the full-fist position. An external load of 50 g was applied to the mid portion of the distal phalanx for all three positions in the mathematical model. A summary of internal tendon forces for the FDP and FDS in these three positions is provided (Table 2). The results of that study suggest that active motion with a 50-g external load in the position of SAM (wrist extension modified for clinical application to 20–30 degrees, MP flexion 75 degrees, PIP flexion 75 degrees, and DIP flexion 40 degrees) is compatible with a standard modified Kessler core suture with an epitendinous repair, but that the position of full flexion is not.

Recent experimental studies support the use of low levels of force (>5 N or 510 g) for postoperative rehabilitation programs. The numbers noted in these mathematical calculations are low and likely in a range consistent with therapeutic loads when internal forces are elevated by the drag of suture material and by variables associated with wound healing.

The magnitude of estimated internal force is considered with respect to the estimated tensile strength of the repair being treated. Strickland provides an excellent review of available repair techniques and their properties in this issue and elsewhere. To estimate the tensile strength of any given repair, the clinician should consult the published values on load to gapping of the combined core and peripheral suture, and then adjust those values to account for the decrease in tensile strength thought to be associated with early tendon healing. Initial repair strength is usually decreased by 50% at the end of the first postoperative week, by 33% at the end of the third postoperative week, and by 20% at the end of the sixth postoperative week, and should be respected with regard to the level of 2-mm gapping because gaps larger than this are associated with higher friction, poorer healing, and increased rupture rates. While we do not know the effects of immediate controlled motion on the repaired human flexor tendon in vivo, immediate constrained digital motion tested experimentally allows progressive healing without the intervening phase of tendon softening or weakening described in earlier classic studies.

The clinical implications from this mathematical modeling are that for all early active motion programs, wrist and finger position for the active exercise component are critical. Force transmission will be reduced in the flexor system if the wrist is in mild extension to decrease resistance from the extensor system and if the digital joints are held in a position of moderate flexion. A position of full composite digital flexion with an early active motion

<table>
<thead>
<tr>
<th>Variable for Calculation</th>
<th>Relaxed Position</th>
<th>Short Arc Motion for LEAF</th>
<th>Composite Fist</th>
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</thead>
<tbody>
<tr>
<td>Wrist position</td>
<td>45° extension</td>
<td>45° extension</td>
<td>45° extension</td>
</tr>
<tr>
<td>MP joint position</td>
<td>40° flexion</td>
<td>75° flexion</td>
<td>85° flexion</td>
</tr>
<tr>
<td>PIP joint position</td>
<td>54° flexion</td>
<td>75° flexion</td>
<td>95° flexion</td>
</tr>
<tr>
<td>DIP joint position</td>
<td>45° flexion</td>
<td>40° flexion</td>
<td>75° flexion</td>
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<td>External load</td>
<td>50 g</td>
<td>50 g</td>
<td>50 g</td>
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<tr>
<td>Internal tendon force FDP</td>
<td>41 g (no drag)</td>
<td>41 g (no drag)</td>
<td>2,050 g (no drag)</td>
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<tr>
<td></td>
<td>82 g (with drag)</td>
<td>82 g (with drag)</td>
<td>4,100 g (with drag)</td>
</tr>
<tr>
<td>Internal tendon force FDS</td>
<td>0 g</td>
<td>605 g (no drag)</td>
<td>1,650 g (no drag)</td>
</tr>
<tr>
<td></td>
<td>0 g (with drag)</td>
<td>1,210 g (with drag)</td>
<td>3,300 g (with drag)</td>
</tr>
</tbody>
</table>

Revised from Evans RB, Thompson DE. 40
protocol will require a tendon repair technique that resists 2-mm gap formation at greater than 4,100 g applied tension during the first three weeks of wound healing; therefore, a position of full composite flexion would require a four-strand core suture with an epitenon suture. The modified position of SAM, as defined in this article, has proven to be compatible with a two-strand core and epitenonous suture. Load to gapping with cyclic stress for the FDP has been measured at 2,280 g if repaired with a modified Kessler (3-0 silk, two-strand core) with the addition of a circumferential suture (6-0 polypropylene)\textsuperscript{[2]}; this number reduced by 50% to factor the anticipated decrease in tensile strength the end of the first postoperative week would equal 1,140 g. Extreme finger positions and rapid finger motions are to be avoided. The stronger repairs are preferable for early active motion, offering a greater “safe zone” between the tensile strength of the repair and internal tendon force applied with therapeutic loads.

**Clinical Application of Active Tension**

In zone I, the passive regimen includes passive flexion of the DIP joint within the confines of the digital splint from 40 to 75 degrees flexion to theoretically effect approximately 3 or 4 mm passive excursion as calculated by radians.\textsuperscript{1} The passive modified hook, passive full fist, and PIP extension, and wrist tendinous exercise may improve differential tendon excursion within the digital sheath and more proximally.\textsuperscript{42,43,86,100–102} The “active hold” exercise for the FDS in the injured digit may help to limit the effects of adhesions associated with ruptured vinculae from profundus retraction, bleeding into the flexor sheath, and surgical trauma from FDP retrieval.\textsuperscript{1} Early active isolation exercise of the FDS tendon may help to avoid PIP flexion contracture.\textsuperscript{21} Under therapist supervision, the hand is removed from the splint for wrist tendinous exercise to improve passive tendon excursion.\textsuperscript{86,100–102} for active tension exercise that may improve breaking strength and enhance cellular activity,\textsuperscript{40} and to provide some true proximal migration of the repair site.

Internal tendon forces are reduced with the SAM protocol by delaying mobilization until inflammation has subsided,\textsuperscript{81} preceding the active exercise component with slow, repetitive passive motions to help displace the high-molecular-weight fluids of edema\textsuperscript{105}; by positioning the wrist in mild extension to reduce the resistance of the antagonistic muscles\textsuperscript{40,104}; by avoiding the end ranges of flexion; and by applying only 15 to 20 g external load (measured with the Haldex pinch meter) with the exercise position of SAM (wrist 20 degrees extension, MP 80 degrees flexion, PIP 75 degrees flexion, DIP 40 degrees flexion\textsuperscript{40}) and by minimizing the speed of motion (Llorens WL. An experimental analysis of finger joint stiffness [MSME thesis]. Baton Rouge: Louisiana State University, 1986).\textsuperscript{52,103,122}

**How Often?**

An experimental study concluded that the frequency of controlled passive motion in postoperative tendon management protocols is a significant factor in accelerating the healing response after tendon repair with regard to tensile properties, as represented by linear slope, ultimate load, and energy absorption, and that higher-frequency controlled passive motion has a beneficial effect.\textsuperscript{123} In a related clinical study, the duration of the daily controlled passive-motion interval has been determined to be a significant variable in a clinical study of repaired flexor tendons, with increased frequency providing superior clinical results with respect to IP motion.\textsuperscript{124}

Patients treated with the LEAF protocol are advised to spend three to five minutes each hour performing the controlled exercise, with the anticipated patient compliance actually being much lower than this.\textsuperscript{125,126}

**SUMMARY**

Limited extension and controlled active tension as described for the repaired zone I flexor tendon flexor tendon repair will be tolerated by both tendon-to-tendon and tendon-to-bone repair; limiting distal joint extension may help to eliminate or decrease gapping at the repair site. The described technique is dependent on a repeatable and reliable application of force within a strictly defined rehabilitation protocol. This technique employs limited excursion and low loads at the repair site, concepts supported by recent experimental research.\textsuperscript{96,98,115,116} Stronger repairs for active motion protocols are preferable, but not always available, and in my experience active tension applied with the defined parameters of the modified fist will be tolerated by conventional suture technique (modified Kessler with epitenon suture) and may be expected to provide improved functional results in terms of active IP joint flexion. Internal tendon tension for the zone I FDP at this level is low with the described positions of exercise.

Inappropriate stress application, PIP flexion contracture, late referral to therapy, and patient noncompliance are variables that can compromise the functional result. The results reported here do not equal the results reported by others,\textsuperscript{9,10,15,58,65,127} but they do represent significant improvement in my own clinical results\textsuperscript{1,40,65} over patients treated with passive regimens and with traction. These cases represent various levels of surgical skill generated by a wide referral base, no controls on repair technique, and combined levels of complexity.
This protocol has been criticized by some as being too complicated. Until we are satisfied that our repair strengths are strong enough to withstand subjective amounts of force applied by the patients, we need to structure their exercise so that stress and excursion are carefully controlled. Four or five maneuvers with stress application presents a less complicated scenario than problems associated with gaping, rupture, or the need for a second repair.

REFERENCES


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