Pyramid of Progressive Force Exercises to the Injured Flexor Tendon

Gail N. Groth, MHS, OTR, CHT
Department of Industry and Manufacturing Engineering
College of Engineering and Applied Science
University of Wisconsin-Milwaukee
Milwaukee, Wisconsin

ABSTRACT: Postoperative rehabilitation for patients who have sustained a laceration to their flexor tendon apparatus is an important factor in maximizing functional outcome. Quality rehabilitation is characterized by the development of a tailored exercise regimen. There is currently no model available to tailor an exercise regimen for a person with an atypical physiologic response pattern. If rehabilitation protocols were classified according to the criteria of forces applied across a tendon juncture and/or excursion, and a clinical method were available to assist in the identification of optimal tendon loading and/or excursion application, then those individuals with atypical response patterns could be treated more efficiently and effectively. The author conducted a literature review and case study. A model for systematic application of progressive loading exercises to the intrasynovial flexor tendon injury and repair is conceptually developed. The model consists of a pyramidal series of eight specific rehabilitation exercises in the following sequence: passive protected extension, place and hold, active composite fist, hook and straight fist, isolated joint motion, resistive composite fist, resistive hook and straight fist, and resistive isolated joint motion. Concepts are developed to implement a three-point clinical adhesion-grading system. Clinical application of the system is highlighted. An excellent outcome was considered 112% total active motion. A model for systematic application of progressive loading exercises has been conceptually developed in concert with a method for determination of optimal tendon loading. Further substantiation is necessary to validate the proposed theory.

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Postoperative rehabilitation for patients who have sustained a laceration to their flexor tendon apparatus is an important factor in maximizing functional outcome. Rehabilitation has been shown to be effective in reducing the impact of restricting intrasynovial adhesions,[1–5] stimulating the restoration of the gliding surface,[6–11] facilitating the healing of the repair site,[12–14] and allowing more complete recovery of digital range of motion.

A tailored regimen of exercise, education, and equipment is a distinctive feature of quality rehabilitation. The melding of unique anatomy, injury, surgery, and physiologic response, notwithstanding psychological response, necessitates an individualized approach in crafting a successful outcome from flexor tendon repair. Despite this widely accepted truth, published clinical series typically advocate one sweeping postoperative regimen or protocol without allowances for individual physiologic tissue or biologic responses. Time-based protocols further compound this issue by giving emphasis to the time lapsed from the date of surgery when prescribing therapeutic exercise, rather than on individual tissue response. Experimental models note variations in response, although scientific models preclude responsive adjustments and espouse clinical implications that are products of aggregate biologic information and exclusive of individualization of tissue response.

Individualized adjustments to postoperative management could be systematically implemented if rehabilitation exercises were sequenced according to the criteria of internal forces applied across the tendon juncture,[15,16] and a clinical method were available to assist in the identification of optimal force application. If such a system were available, those individuals with atypical biologic response patterns could be treated more efficiently and effectively with less fear of tendon rupture and/or restricting peritendinous adhesions.

The purpose of this article is to develop a model of progressive therapeutic exercise along the criterion of

Correspondence and reprint requests to Gail N. Groth, MHS, OTR, CHT, 1406 Beacon Drive, Watertown, WI 53098. E-mail: <davegroth@mindspring.com>.

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forces applied across the tendon juncture, considering excursion requirements, through a review of the literature. Furthermore, a clinical method is introduced to determine optimal tendon loading, which will facilitate individualized rehabilitation of the healing flexor tendon.

MODEL OF PROGRESSIVE THERAPEUTIC EXERCISE

Progressive force application to the healing flexor tendon juncture is theorized as a series of eight specific rehabilitation exercise levels. These exercises are conceptualized in a pyramid format with the base of the pyramid signifying the lowest level of force across the juncture as well as exercises that are performed with the highest frequency. (Figure 1). Loads rise as the pyramid builds, although the frequency of prescription decreases. Patients begin force application at the lowest level progressing upward only as determined necessary, reaching maximum loads, i.e., the pinnacle of the pyramid, on an infrequent basis. The uniqueness of this approach lies in the prescription of specific levels of load according to tendon performance rather than uniqueness in the exercises themselves.

Passive Protected Digital Extension Level

This level encompasses the passive finger exercises first described by Duran and Houser.[17] Passive flexion and extension of the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints are performed independently and then in a composite fashion. With this exercise, the position of the wrist varies in a synergistic pattern (i.e., flexed as the fingers are extended, extended as the fingers are flexed).

Internal Tendon Loads

Urbaniak et al.[18] and Schuind et al.[19] placed a force transducer on healthy patients undergoing carpal tunnel release and found that passive digital flexion–extension caused internal tendon forces ranging from 2 to 3 N and 0.1 to 3 N, respectively. Experimental findings in a canine model range from 4 N[16] to 15–25 N.[20]

Several investigators have shown that internal flexor tendon load is highly dependent on the wrist position,[15,16,20] altering linearly with changes in wrist joint angle. Tendon loading occurs during wrist flexion as passive digital extension causes the tendon to move distally. Conversely, increased internal loading occurs during wrist extension (and passive digital flexion) as the tendon is pulled proximally.

This level of exercise would be classified as low force/low excursion if the wrist were maintained in flexion and high force/high excursion if the wrist were synergistically moved into extension during passive finger flexion exercises.[15,16]

Excursion

Total available FDP excursion is defined by the sum of tendon displacement in both a proximal and distal direction. At the digital level, excursion varies from 3 to 8 mm in *in vivo* models[17,21,22] to 3.5 to 17.3 mm in canine models [16,20,23–26] to 8 to 33 mm[27–29] in cadaver models. Although high levels of excursion may theoretically be available, it is thought that minimal displacement (1.7 mm) is sufficient to prevent excessive tethering or binding adhesions.[30]

Separation of total excursion into its core components of flexion and extension excursion allows several important considerations.[20] Extension excursion provides the bulwark of advantageous displacement, and the application of cyclic extension excursion prevents restrictive adhesions.

Actual flexor digitorum profundus (FDP) flexion excursion is thought to be minimal in an injured digit. This is the result of numerous factors that heighten tendon gliding resistance, including a fixed wrist position,[15,20] decreased passive range of motion,[31–33] injury distal to the A3 pulley,[34] poor pulley integrity,[25] gapping, bulging, or triggering of the repair, postoperative edema, and size and shape of the joint (moment arm).

Clinical Application

This exercise is often prescribed for patients during their first postoperative visit and continues for the duration of protective splinting. The recommended frequency of exercise is as often as feasible, but no less than four to five times a day. The value of performing passive finger flexion lies in the delivery

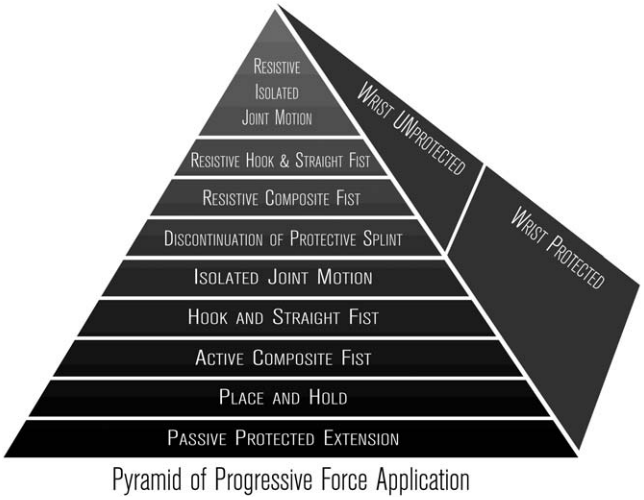

FIGURE 1. *Progressive force exercises to the intrasynovial flexor tendon injury and repair.*

of motion stress defined as the load placed across the tendon juncture during active tendon excursion as well as in the maintenance of finger joint mobility. For those patients whose wrist is immobilized by a protective splint, it is beneficial to remove the splint in the clinic to allow moderate wrist extension during passive finger flexion and moderate wrist flexion during passive finger (PIP and DIP joint) extension. Compliance behavior is a primary factor in considering whether to prescribe the removal of the splint for home exercise.

Place and Hold Finger Flexion Level

This level is a slight modification of the exercise first described by Evans and Thompson.[35,36] Preceding this exercise is a warm-up of slow, repetitious passive flexion and protected extension motions with the wrist positioned in 20° extension. The active hold position reduces viscoelastic drag on the tendon juncture. The metacarpophalangeal (MP)/PIP/DIP digital joints are subsequently actively held in a moderately flexed position.

Internal Tendon Load

Evans and Thompson calculated internal forces on the FDP to vary from 3 to 9 N when the MP, PIP, and DIP joints vary from 68 to 85°, 65 to 95°, and 52 to 65°, respectively. Their math model includes the variables of joint angle, torque analysis, and elastic and viscous resistance. This model, however, does not account for an unknown number of variables that can affect internal tendon loads.

Excursion

Excursion has not been specifically measured for this level of exercise. Extrapolations of Silverskiold et al.'s[21,37] *in vivo* data obtained at the digital level would have 2–10 mm of FDP excursion occurring during active hold of a loose fist (60/80° DIP/PIP flexion).

Clinical Application

This place and active hold exercise is prescribed for patients with two- or four- strand solid repairs during their first postoperative visit and continues until just after progression to the next level of exercise. The frequency of exercise is dependent on compliance behavior and physiologic tissue response, but is typically prescribed for three to five times a day. The value of performing this exercise lies primarily in the early detection of a suboptimal response to motion stress (as demonstrated by very little DIP flexion of 0–5° or, in the other extreme, 50+°) followed by a tailored response. Motion stress is lower when collagen levels, the building blocks of both the loading capacity of the repaired tendon and also of restrictive adhesions, are lower during the early postoperative period. Careful tailoring of the education and home exercise program begins at this level through the considerations of compliance behavior and physiologic response. Adjustments in exercise frequency, splint use during exercise, and positioning of proximal joints are but a few of the additional considerations that play a critical role in the larger picture of successful rehabilitation.

Active Composite Fist Level

This level combines the performance of active digital flexion to the distal palmar crease with the wrist in slight extension (Figure 2).

Internal Tendon Load

Greenwald et al.'s[38] cadaver model and Urbaniak et al.'s[18] healthy hand model produced similar values of 4–9 N and 9–12 N of forces on the FDP tendons, respectively. Evans' math model[35] and Schuind et al.'s healthy hand model[19] produced higher values of 20–40 N and 20–29 N, respectively. Several researchers have used the value of 20 N to replicate the loads tolerated during active digital flexion.[24,39,40]

Excursion

Maximum FDP excursion is achieved at this level with respect to sheath and bone. Total available FDP excursion measured at the digital level varies from 5 to 8 mm[32] in an *in vivo* model and 17 mm[28] in a cadaver model. If available excursion increases, the more proximal the injury.[21,31,32,36]

There is a linear relationship between tendon excursion and joint position i.e., greater excursion occurs with greater digital flexion arc. An *in vivo* study found 0.3 mm/1.2 mm FDP excursion per 10° of controlled motion of the DIP/PIP joint.[36] This

FIGURE 2. *Active composite fist. Photograph courtesy of Milliken Hand Rehabilitation Center, St. Louis, MO.*

extrapolates into 2.1 mm/10 mm FDP excursion with the DIP/PIP joints nearly fully fisted (70/100° of flexion).

Clinical Application

This and all subsequent levels of exercise are prescribed for patients with an *unresponsive* active tendon lag (Table 1) and continues until discharge. This exercise might be prescribed as early as during the second week (third or fourth session) of rehabilitation if the tendon lag is deemed *unresponsive*. If a lag never occurs, this exercise is delayed until 8 weeks postoperatively. In this case, no further progression on the pyramid will likely be prescribed to minimize the risk of rupture or gap formation. Frequency of exercise is dependent on compliance behavior and necessary activities of daily living, but is typically prescribed three to five times a day. The value of initiating this exercise using this system is twofold: excessive load application at the tendon juncture is prevented in one patient, and a high level of tendon gliding resistance is overcome in the patient with binding adhesions.

Hook and Straight Fist Level

This level encompasses the exercises described by Wehbe and Hunter.[41,42] The hook fist position entails maximum flexion of the PIP and DIP joints, whereas the MP joint is maintained in extension (Figure 3). The straight fist position requires maximum flexion of the MP and PIP joints while the DIP joint is maintained in extension.

Internal Tendon Load

Greenwald et al.[38] reported 10–13/8–11 N of forces on the FDP during the hook/straight fist positions. The placement level of this exercise within the pyramidal structure relies on the relative increases, which Greenwald noted from the previous level, rather than from the values Evans[35] and Schuind et al.[19] proposed. No other model has been applied to these positions, leaving an insufficiency of information.

Excursion

Despite the paucity of force data, several investigators have attempted to define FDP/FDS tendon excursion for this level of exercise. The hook fist position causes maximum differential excursion between tendons up to 23–33 mm.[37,40,41] The straight fist position causes maximum FDS gliding between the sheath and the bone and causes excursion that varies from 17 to 30 mm.[37,40,41]

TABLE 1. **Adhesion-grading System**

Absent	≤5° discrepancy between digital active and passive flexion
Responsive	≥10% resolution of active lag between therapy sessions
Unresponsive	≤10% resolution of active lag between therapy sessions

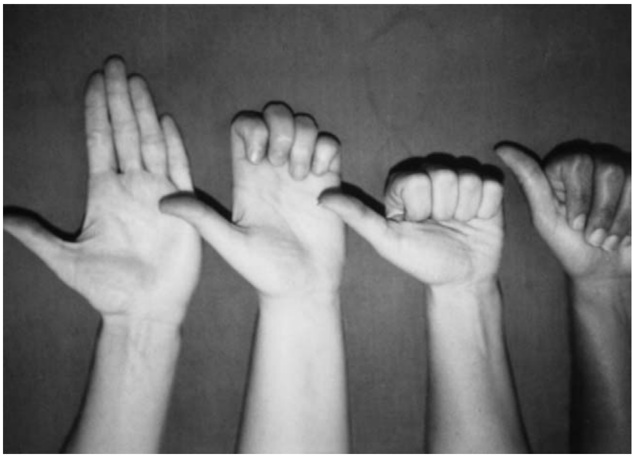

FIGURE 3. *Hook, composite, and straight fist positions. Photograph courtesy of Milliken Hand Rehabilitation Center, St. Louis, MO.*

Clinical Application

The frequency ratio of exercise for the hook fist and straight fist positions is 2:1 as a result of greater loads during motion stress in the former exercise. Great care is taken to achieve full protected (PIP/DIP joint) or complete (MP/PIP/DIP joint) extension between each exercise, and to tailor the wrist position to accommodate the individual's needs. Alternating wrist extension/flexion in a synergistic pattern provides greater stress in the finger flexion positions, whereas maintaining the wrist in neutral or slight flexion minimizes the motion stress delivered.

Isolated Joint Motion Level

External stabilization of the proximal and middle phalanges allows for isolated DIP joint motion and FDP function (Figure 4). External stabilization of the proximal phalanx allows for DIP and PIP joint motion while blocking the MP joint and lumbrical function (Figure 5). Isolated FDS function is obtained when the DIP and MP joints are externally stabilized and the PIP joint is allowed free movement.

Internal Tendon Load

Schuind et al.[19] report that "active unresisted flexion" of the index DIP joint ranged from 1 to 29 N with a mean of 19 N. Their methods make no mention of external stabilization, and therefore, it is unclear if these values represent isolated motion as previously defined.

FIGURE 4. *Isolated distal interphalangeal joint motion. Photograph courtesy of the Milliken Hand Rehabilitation Center, St. Louis, MO.*

Clinical observations demonstrate that the application of external blocking forces can be highly variable during this level of exercise. Experimental data[19,37,43] have demonstrated a linear relationship between external and internal loading of the flexor tendons. Therefore, the level of internal load transmitted to the FDP tendon during this exercise is highly variable. Allowance for this factor places internal flexor tendon force loading during isolated exercise higher on the pyramid than hook or straight fisting.

Excursion

There are no data available to quantify the effect this level of exercise has on FDP tendon excursion.

Clinical Application

The prescription of isolated PIP joint (blocked MP *and* DIP joints) exercise is often overlooked in the patient with a single laceration to the FDP tendon, yet can provide assistance in maximizing motion stress to the adhesions affecting it. Again, great care is taken to achieve full extension of the joint between each exercise, which benefits extension excursion. If the patient overly strains against the blocking mechanism, this exercise degenerates into an isometric condition and is to be avoided.

FIGURE 5. *Isolated proximal interphalangeal joint motion. Photograph courtesy of the Milliken Hand Rehabilitation Center, St. Louis, MO.*

Discontinuation of Protective Splinting

This level of the pyramid is intended to signify the ultimate discontinuation of protective splinting. Significant increases in functional use, and therefore load requirements, naturally occur when the hand is freed from restriction. Progression along the exercise pyramid is suspended while the hand adapts to these increased forces. A useful clinical technique is to grade the discontinuance of protective splinting over a week to reduce sudden motion stress on the hand.

Resistive Composite Fist Level

This level of exercise incorporates isokinetic active composite flexion of the digits with an external mode of resistance. Common expression entails resistive putty fisting and/or squeezing a gripper (Figure 6).

Internal Tendon Load

Urbaniak et al.[18] report 49 N of force on the FDP with "maximum effort" and Schuind et al.[19] report 19–63 N during "grasp" (methodologically ill-defined terms in both cases, as there was no mention of external resistance). Aoki et al.[44] assume the FDP tendon generates 63–65 N of force during "grip and lateral pinch," basing their assumption on Urbaniak et al.'s and Schuind et al.'s reports. Again, several investigators have demonstrated that internal tendon forces vary proportionally,[19,42,45] if not linearly,[37] with external loading.

FIGURE 6. *Resistive composite fist. Photograph courtesy of the Milliken Hand Rehabilitation Center, St. Louis, MO.*

Extrapolation of Greenwald et al.'s[38] and Dennerlein et al.[43] linear data would show 372 N and 862 N, respectively, of internal force on the FDP tendon during a moderate 20-kg grasp of a dynamometer.

Excursion

Greenwald et al.[38] demonstrated that tendon excursion varies sigmoidally (an S-shaped curve) with grip strength (force loading). They reported that as grip strength/tendon excursion increased beyond 9.8 N/1.8 mm, the curves became almost linear as the slack in the flexor system was taken up. In application, this would mean that if 10–15 N of external force were applied to resistive putty, excursion would theoretically be less than two tenths of one millimeter.

Clinical Application

The amount of force applied to resistive putty is observed to be highly dependent on the speed at which it is compressed. Slower compression requires less force, whereas rapid compression requires greater force. Grippers provide different end range positions for the digits or can be adapted for that purpose. Thoughtful application of these features provides useful variety in exercise prescription. Resistive finger extension exercise can also be beneficial in reducing intrasynovial adhesions and increasing extension excursion.

Resistive Hook and Straight Fist Level

This level uses the positions described previously with the application of an external mode of resistance (Figure 7). Care is taken to vary the location of the finger joint angles and the position of the wrist during primary resistance. This maximizes force application.

Internal Force Load

There is no tendon load data available for this level. If the previous relationship of hook/straight fisting to composite fisting is accepted, then it can be extrapolated that this level requires more load than resistive composite fisting.

Excursion

There is no excursion data available. It is thought that little additional tendon excursion occurs at this level if Greenwald et al.'s[38] excursion/force data are extrapolated to higher force application.

Clinical Application

This level and the next are seldom indicated when early motion stress has been correctly applied

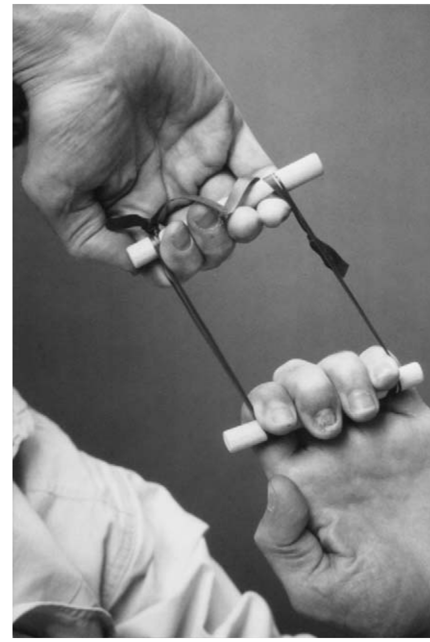

FIGURE 7. *Resistive hook fist. Photograph courtesy of Pattie Paynter and Pam Schindeler-Grasse for Milliken Hand Rehabilitation Center, St. Louis, MO.*

to a healing tendon. However, when necessary, attentive creativity will produce many options regarding the mode of delivery and the position of proximal joints. The elimination of exercise redundancy and the prioritization of the home exercise program are critical factors to maintain compliance behavior at this level. Sensitivity to the amount of prescribed exercise may serve to maintain motivation and commitment to the process of rehabilitation.

Resistive Isolated Joint Motion

This level incorporates the positions described previously and applies an external mode of resistance (Figure 8). Again, care is taken to vary angles of proximal joints during primary resistance to maximize force application. Such variance creates a minimum of 12 exercise positions for the digit: four for the DIP joint (wrist/MP flexed/extended) and eight for the PIP joint (wrist/MP flexed/extended, DIP blocked/free). Multifarious modes of external resistance increase the number of potential exercises even further. Alba and LaStayo[46] were the first to publish a case report clearly describing a maximal loading exercise for an adhered flexor tendon. Their case report identified *unresponsive* lags of the flexor pollicis longus (FPL) and digital flexor tendons. One of their prescribed exercises used a custom-made splint to place the adhered flexor tendons on passive stretch (wrist, MP, PIP joint extension) followed by a dynamic component for resistive DIP flexion.

FIGURE 8. *Resistive isolated joint motion. Photograph courtesy of Pattie Paynter and Pam Schindeler-Grasse for Milliken Hand Rehabilitation Center, St. Louis, MO.*

Internal Tendon Load

There are no load data available, but the previous force relationships establish the placement of this level of exercise above those described earlier.

Excursion

There are no excursion data available.

Clinical Application

If the active lag remains unresponsive within two weeks after the prescription of this exercise, the patient has achieved maximum benefit from supervised rehabilitation and is discharged.

DETERMINATION OF OPTIMAL LOAD APPLICATION

Optimal load application is considered to be the mediation between loads that are too low and loads that are unnecessarily high. Load application is too low if the healing tendon is unable to overcome the factors contributing to tendon gliding resistance.[20] These factors include, but are not limited to, concomitant injuries to the surrounding tissues,[47,48] early wound healing,[49–51] placement of sutures,[52] and friction within the joints or pulleys.[53–56] Edema predestines increased viscous–elastic resistance.

Load application is unnecessarily high if the transmitted loads across the tendon juncture risk exceeding either the breaking strength of the repair or the strain tolerated at the repair site. Yet, high levels of loads are advocated by the preponderance of experimental and clinical studies. Recent studies have shown that increasing levels of force application do not contribute to healing, suture rigidity, or increased levels of *in vivo* tendon strength.[38,57]

One clinical indicator of the transmission of suboptimal loads is the presence of binding collagenous adhesions. Adhesion formation is clinically indicated by a discrepancy between active and passive range of motion (ROM).[58] The severity of *in vivo* adhesions and clinical active flexion lags has remained largely undefined. Recently Zhao et al.[20] have suggested that *in vivo* adhesions may be classified on a five-point scale from "none" to "very severe." Collins and Schwarze[59] used a 50° discrepancy between active and passive ROM in the clinic to indicate dense adhesions. They go on to differentiate between patients whose lags lessen from the 50° benchmark and those whose adhesions were not responding (to motion stress).

A clinically useful method that evaluates the presence and severity of adhesions is proposed. This method identifies the presence of an active flexion lag and subsequently determines its responsiveness to motion stress (Table 1). This model of classification provides the basis for systematic application of motion stress to the healing flexor tendon during postoperative rehabilitation. More specifically, if there were no active flexion lag (*absent*), load application would remain minimal, i.e., at the lowest level on the pyramid. If the lag were *responsive* to stress application as determined by goniometric ROM measurements, load application would remain at the existing level on the pyramid throughout the remainder of the 12-week rehabilitative period. If the lag were *unresponsive*, then load application would increase one level per rehabilitation session (with the assumption that the patient attended rehabilitation one to two times a week).

CASE REPORTS

Case 1

The following case presentation (limited to load application) illustrates how the load pyramid and the adhesion-grading chart might be applied clinically to a patient with an atypically low physiologic response pattern.

A 31-year-old male professional athlete injured his dominant ring finger as he grasped a sharp knife, completely lacerating both flexor tendons and his radial digital nerve in zone II. He underwent surgery later that day with an eight-strand core suture and an epitendinous suture placed in his FDP tendon, one slip of the FDS with a two-strand suture, and a digital nerve repair.

A synergistic hinge-splint was fabricated on day 2 postoperatively, and the patient was instructed in

TABLE 2. Sequence of Therapeutic Exercise: A Literature Review

Pyramid Levels	Silverskiold[37]	Evans[36]	Indiana[94]	Dovelle[96]	Gratton[93]	Collins[59]	Chow[76]
Passive protected extension	1	1	1	1	1	1	1
Place and hold	*	1	1	*	*	*	2
Active composite fist	2	2	2	2	1	2	2
DTG	4	*	3	*	*	2	3
Isolated joint motion	4	*	4	3	*	3	*
Resistive composite fist	3	*	5	*	*	4	*
Resistive DTG	*	*	*	*	*	*	*
Resistive isolated joint motion	*†	*	*	*	*	*	*

*No mention of exercise in publication.
†Power grip.
DTG = differential tendon gliding.

passive tenodesis and Duran's passive finger extension and flexion exercises. Several repetitions of place and hold were performed to obtain goniometric active hold measurements of −5/85° at the PIP joint and −5/54° at the DIP joint. No active lag was present and optimal load application was considered to be the lowest level, i.e., passive protected extension. He was instructed to continue this regimen at home.

At each subsequent biweekly rehabilitation session, place and hold values continued to increase until the PIP and DIP measurements at week 8 were 0/103° and 0/74°, respectively. Optimal force application, with the absence of any flexion lag, was determined to be limited to the two lowest levels of the pyramid. The synergistic splint was discontinued and active composite flexion initiated during the eighth week.

Discharged at 14 weeks postoperatively with an excellent result (112% total active motion) according to Strickland's formula and classification system, this patient never progressed beyond simple fisting exercises. Remarkable particulars regarding the postoperative period included slow wound healing (four weeks), absence of edema, and excellent mastery and presumed compliance of the synergistic exercise.

Case 2

High Physiologic Response

A 52-year-old male worker injured his dominant hand/wrist when he fell onto the sharp edge of a steel rack, completely lacerating the flexor carpi radialis, flexor carpi ulnaris, and flexor digitorum superficialis tendons to his index, long, and ring digits in zone V. All structures were surgically repaired later that day with two-strand repairs.

A custom splint was fabricated on day 2 postoperatively, and the patient was instructed in passive finger extension and flexion exercises. He was progressed to active composite fisting per surgeon's order at 11 days postoperatively despite good active ROM. Protective splinting was discontinued at four and a half weeks postoperatively. The therapist prescribed the remainder of the pyramid steps when the flexion lags were considered unresponsive as summarized in Table 3.

The patient was discharged at 14 weeks postoperatively with excellent results (index/long/ring = 100%/102%/106%, wrist extension/flexion = 62/55°) according to Strickland's formula and classification system. He progressed quickly through the pyramid despite only having a two-strand repair. Remarkable particulars regarding the postoperative period included edematous fingers, generalized soreness and morning stiffness, and the temporary reduction in goniometric measures during the course of rehabilitation.

DISCUSSION

Rehabilitation is delivered through the application of motion stress to the repair site and is clinically conveyed through tendon loading and tendon excursion. Remaining indistinct is the role of tendon

TABLE 3. High Physiologic Response Case

Joint AROM	Active Fist (1 week 4 days)	Hook & Straight Fist (4 weeks 2 days)	Resistive Fist (7 weeks 2 days)	Discharge (14 weeks 2 days)
Index PIP	0/95	−20/75	−10/95	−10/108
Index DIP	0/48	0/30	0/50	0/77
Long PIP	0/95	−15/82	−10/95	−10/108
Long DIP	0/55	0/67	0/66	0/80
Ring PIP	0/125	−15/85	−8/95	−2/108
Ring DIP	0/60	0/50	0/65	0/80

PIP = proximal interphalangeal joint; DIP = distal interphalangeal joint; AROM = active range of motion.

loading in restoring digital range of motion. The beneficial role of excursion, however, has been established explicitly through experimental studies.[17,60–63] The relative contributions of tendon loading and tendon excursion to a functional outcome is also ill defined. Given the anatomic nature of the flexor tendons (which exist as one portion of a binary musculotendinous unit), it is presumed that a relationship exists between muscle force and tendon excursion. If this is accepted, then optimal tendon loading occupies a critical role, alongside excursion, in the limitation of intrasynovial flexor tendon adhesions.

Immoderate tendon loading also risks the evolvement of gap or suture rupture. Several investigators have found the prevalence of gap formation at the site of flexor tendon repair to be substantial.[32,64–67] The effects of gap formation, however, are undetermined. Some authors report that gap formation is associated with increased adhesions.[32,62–64,68] Others have noted that early motion inhibits the formation of excursion-limiting adhesions and negates the effect of gap formation on digital motion.[21,30,36,66] More recent studies report that small gap sizes of ≤3 mm may not have an injurious effect on active ROM.[24,30,36,38,66]

There are no guidelines currently available to assist in navigating between overcoming tendon gliding resistance and avoiding excessive tendon loading,[26] because successful navigation through this furrow is an inherently individual process. Without individualized guidelines, there is an impasse in maximizing outcomes, because individualized treatment is the hallmark of good rehabilitation.[22,69]

Time-based protocols do not adequately address successful navigation between overcoming gliding resistance while avoiding excessive tendon loading. The conceptual bulwark of time-based protocols came from the work of Mason and Allen[70] and Urbaniak et al.,[18] who demonstrated that repaired tendons experience a softening period. Potenza[71,72] contributed to the time-dependent attributes of healing tendons when he reported that tendons healed extrinsically through tendinous adhesions. Postoperative protocols sensitive to these incremental periods of time were developed, including controlled passive motion[73] and Kleinert-type regimens.[74–79] More recently, several investigators have found that tendon softening has not occurred when tendons are subjected to motion stress throughout the healing period,[8,38,80] and tendons heal intrinsically as well as extrinsically.[81–85] Protocols that reflected our heightened understanding were developed, including early active motion regimens,[35,86–93] synergistic regimens,[94] and various combinations of these components.

The sequence of therapeutic exercises for presumed progressive tendon loading varies slightly in published series (Table 2). Most notably, progressive resistive exercises have not reportedly been applied to the highest levels of the pyramid. Much literary discussion exists regarding standard and early rehabilitation, with only Collins and Schwarze[59] addressing adhesed tendons.

The development of the concepts in this article is in response to the postoperative trend of increasing motion stress on the repair site and surrounding tissues over the past decade.[95] Recent experimental findings regarding the impact of wrist position on loads across the tendon juncture and tendon excursion obviates regimens that immobilize the wrist. Synergistic protocols are sensitive to the criteria of load and excursion, yet continue to advocate high levels of tendon loading regardless of individual tissue response.

The clinical application of the load pyramid is feasible for use with any existing protocol. It is not limited to a particular zone of injury, type of suture repair, timing of initiation after surgery, or type of protective splint. Rather, the concept it uses for motion stress is wrapped around current practice and, in the typical response pattern, does not differ significantly from many popular regimens.

Limitations of the conceptualization of the load pyramid include a lack of attention to other parameters involved in successful rehabilitation. These include, but are not limited to, the identification of motivational issues and health beliefs, tailored patient education programs, attention to protective splint geometry, edema management, and external stress application to scars. It does not specifically address excursion requirements. In addition, the force pyramid is theoretical with limited clinical data and needs to be substantiated by more robust experimental and clinical data.

CONCLUSIONS

A model of eight progressive therapeutic exercises along the criterion of forces applied across the tendon juncture, considering excursion requirements, was developed through a review of the literature. An adhesion-grading system determines optimal tendon loading, which provides the guidelines for using the pyramid in clinical practice. The utilization of this system provides a systematic method for individualizing treatment of the patient with a healing flexor tendon. Two case studies are presented. The sequence and relevance of the therapeutic exercises contained in the pyramid need to be substantiated through further experimental and clinical research.

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