Regaining satisfactory digital function after flexor tendon laceration and repair within the digit has long been one of the most difficult problems in hand surgery. Until the 1960s it was universally recommended that tendons divided in the digit (then referred to as "no man’s land") should not be repaired. Bunnell taught that "it is better to remove the tendons entirely from the finger and graft in new tendons smooth throughout its length."1 That dictum remained sacrosanct until the 1960s when reports by Verdan,2,3 Kleinert et al,4 and Kessler and Nissim5 challenged the concept that flexor tendons should not be repaired primarily. These investigators noted that when done correctly, immediate tendon suture would outperform secondary free tendon grafting. Armed by those encouraging reports, there was a gradual and cautious development of the concept and practice of primary flexor tendon repair. Initially, primary tendon repair was often combined with anecdotal protocols by Duran et al,6 Lister et al,7 and Strickland and Glogovac8 for applying varying amounts of early post-repair motion to the repaired tendons.

As often happens with advances in medicine, the efforts to improve the performance of flexor tendon repairs were based almost entirely on individual experience and clinical experimentation with little or no scientific support. The last 25 years, however, have heralded an enormous amount of basic research designed to improve our knowledge of the structure of tendons, including the kinesiology, the biomechanics of their action on the joints they move, their biologic response to injury and repair, the mechanical characteristics of various tendon suture constructs, and the effect of post-repair motion stress on tendon strength and healing. These investigative efforts have given rise to improved methods of tendon repair, a greater emphasis on flexor sheath preservation and restoration, and protocols for the early application of passive and active wrist and digital motion as a means to more rapidly increase the strength and gliding of repaired tendons. The following sections will provide a concise review of some of the most important of these reports.

**Basic Science of Flexor Tendon Surgery**

**Flexor Tendon Morphology**

Many recent studies have investigated biology, histology, innervation, lymphatic drainage, ultrastructure, biochemical composition, physical characteristics, energy storage, and response to loading of the normal and injured animal and human tendon and tendon sheath. Much of this work has been summarized by Gelberman et al,9 and this body of laboratory information has proven to be extremely valuable to the clinician’s efforts to improve results.

In summary, tendons are composed of approximately 70% molecules made up of peptide chains in a triple helix configuration (tropocollagen). Tendon fascicles consist of long, narrow, spiraling bundles of
mature fibroblasts (tenocytes) and type I collagen fibers. The surface of the individual bundles of collagen is covered by the endotenon; externally, the septa of the endotenon join together to form a fine fibrous outer layer, the epitenon, that covers the surface of the tendon. In the hand, the flexor tendon fascicles are covered by a thin visceral and parietal adventitia, the paratenon, that is associated with a fluid environment similar to synovial fluid.

Flexor Tendon Anatomy

While historic anatomic descriptions of flexor muscle tendon anatomy have largely stood the test of time, recent investigations have added greatly to our understanding of the restraint system within the digit. Flexor tendon sheaths, with their predictable annular pulley arrangement (Fig. 1), serve not only as a protective housing for the tendons, but also provide a smooth gliding surface by virtue of their synovial lining and an efficient mechanism to hold the tendons close to the digital bone and joint. Although there is some controversy about the exact anatomy and nomenclature of the elements of the flexor tendon sheath, the original descriptions of Doyle and Blythe10–14 as supplemented by the findings of Hunter15 and Manske and Lesker16 (aponeurosis pulley) remain the accepted “working” system for most hand surgeons.

Flexor Tendon Nutrition

Studies during the last 25 years have added to some existing understanding of the nutrition of flexor tendons. Studies by Armenta and colleagues,17,18 Azar et al,19 Caplan et al,20 Chaplin,21 Hooper et al,22 Hunter,15 Lundborg and colleagues,23–27 Manske and colleagues,28–31 Ochiai et al,32 Peterson et al,33 Weber,34,35 and Zbrodowski et al,36 among others, have established an understanding that tendons receive nutrition from both vascular and synovial sources. The vascular perfusion of flexor tendons is provided by longitudinal vessels that enter in the palm and extend down intratendinous channels, vessels that enter at the level of the proximal synovial fold in the palm, segmental branches from the paired digital arteries that enter in the tendon sheaths by means of the long and short vincula, and vessels that enter the flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP) tendons at their

Figure 1. Lateral (top) and palmar (bottom) views of a finger depict the components of the digital flexor sheath. The sturdy annular pulleys (A1, A2, A3, A4, and A5) are important biomechanically in keeping the tendons closely applied to the phalanges. The thin, pliable cruciate pulleys (C1, C2, and C3) collapse to allow full digital flexion. A recently described addition is the palmar aponeurosis pulley (PA), which adds to the biomechanical efficiency of the sheath system.
osseous insertions. Both tendons have relatively avascular segments over the proximal phalanx; the profundus has an additional short avascular zone over the middle phalanx (Fig. 2).

Synovial fluid diffusion provides an effective alternative nutritional and lubricating pathway for flexor tendons. The rapid delivery of nutrients is apparently accomplished by a pumping mechanism known as imbibition in which fluid is forced into the interstices of the tendon through small conduits in the tendon surface as the digit is flexed and extended. The clinical importance of these nutrition studies relates to an appreciation that the biologic response to injury and the healing of repaired flexor tendons may be substantially affected by injury to the vascular and tissue fluid nutritional systems. Because these nutritional sources are vital to rapid tendon healing and the restoration of gliding, it is imperative that the surgeon respect their integrity during all reparative efforts.

Biomechanical Properties of Flexor Tendons

In recent years much has been done to study the normal and injury-altered mechanics of the human flexor tendon system. In particular, the work of Amadio et al., Brand and colleagues, Doyle and Blythe, Hume et al., Idler, Lin et al., Mitsionis et al., Peterson et al., Phillips and Mass, Pring et al., Thompson and Giurintano, Walbeehm and McGrouther, and Zissimos et al. has made us appreciate the importance of preserving and restoring the normal anatomy and function of the flexor tendon system.

The greater the distance a tendon is from the axis of joint rotation, the greater the moment arm and the less motion that a given muscle contraction will generate at that joint. Conversely, a shorter moment arm will result in more joint rotation from the same tendon excursion. The moment arm, excursion, and joint rotation produced by the flexor tendons is governed by the constraint of the pulley system. Loss of portions of the digital pulleys may significantly alter the normal integrated balance between the flexor, intrinsic, and extensor tendons. The A2 and the A4 pulleys are the most biomechanically important; the loss of a substantial portion of either may diminish digital motion and power and lead to flexion contractions of interphalangeal joints (Fig. 3).
Flexor tendon excursion studies by Horibe et al., McGrouther and Ahmed, and Wehbe and Hunter indicate that as much as 9 cm of flexor tendon excursion may be required to produce composite wrist and digital flexion, while only approximately 2.5 cm is required for full digital flexion with the wrist stabilized at neutral (Fig. 4).

The pressure between the normal digital pulleys and the flexor tendon may be considerable during active flexion according to experimental measurements reported by Lin et al. and Manske and Lesker. In addition, the frictional forces existing between normal and sutured gliding tendons have been reported by An et al., Coert et al., and Uchiyama et al.

From studies conducted by Bright and Urbaniak, Evans and Thompson, Greenwald et al., and Schuind et al., it appears that during unresisted passive flexion, flexor tendons are subjected to 2 to 4 N of force. Active flexion with mild resistance may result in up to 10 N of force, moderate resisted flexion in up to 17 N, and strong composite grasp in up to 70 N; firm tip pinch can apparently generate as much as 120 N of tensile load on the index FDP. Schuind et al. have demonstrated that the forces produced by the FDS tendon are less than those produced by the FDP during grasp and pinch. The forces required to produce full excursion and the work (force \times distance) of flexion are increased significantly after flexor tendon repair according to study results reported by Aoki et al., Halikis et al., and Lane et al. The information from these studies can help generate force estimates that can be plotted against strength estimates of various flexor tendon repairs to determine the relative safety of post-repair motion protocols during the healing process.

Tendon Healing

In the last 3 decades there have been an enormous number of published investigations dealing with the biology of the tendon healing process. Convincing studies by Becker et al., Garner et al., Gelberman et al., Lundborg and Rank, Manske et al., Mass and Tuel, Matthews and Richards, McDowell and Snyder, and Umeda have dispelled the previous concept that tendons lacked the intrinsic biologic capability to participate in their own healing. Almost all students of tendon healing now believe that tendons have both an intrinsic and an extrinsic capability to heal and that the relative contribution of each will depend on factors that relate to the injury and the surgical repair.

In the clinical setting it is impossible to isolate the 2 types of healing and the cellular events are similar for all flexor tendons (Fig. 5). Tendon healing involves an inflammatory phase from 48 to 72 hours.
after repair, a fibroblastic- or collagen-producing phase from 5 days to 4 weeks, and a remodeling phase that continues until approximately 112 days. During the inflammatory phase of tendon healing the strength of the repair is almost entirely that which is imparted by the suture itself with a modest contribution from the fibrin clot between the tendon ends. Strength increases rapidly during the fibroblastic collagen-producing phase when granulation tissue is formed in the defect. When extrinsic healing predominates, adhesions between the tendon and its surrounding tissues are inevitable while healing that is largely based on intrinsic cellular activity will result in fewer, less-dense adhesions.

A large amount of research is currently being conducted in an effort to understand the influence that soluble polypeptides, including growth factors, hormones, and chemotactic factors such as fibronectin, exert on the cellular sequence of tendon healing.\textsuperscript{91–100} These factors play a role in both normal and pathologic processes, and their clinical manipulation may greatly improve the outcome of tendon repair and rehabilitation.

Externally applied modalities have been used in an attempt to favorably alter flexor tendon healing. Gan et al\textsuperscript{101} and Roberts et al\textsuperscript{102} studied the effects of ultrasound, Fujita et al\textsuperscript{103} evaluated constant direct electrical current, and Greenough\textsuperscript{104} used pulsed electromagnetic fields. Although these methods have promise, none has yet found its way into the post-repair armamentarium of most hand surgeons.

In a series of outstanding laboratory experiments and reviews, Gelberman and colleagues\textsuperscript{9,105–109} demonstrated that the application of early passive motion stress to repaired canine tendons led to a more rapid recovery of tensile strength, fewer adhesions, improved excursion, better nutrition, and minimum repair site deformation compared with immobilized tendons. These investigators concluded that passive mobilization enhances healing by stimulating maturation of the tendon wound simultaneously with the remodeling of tendon scar. Hitchcock et al\textsuperscript{110} and Aoki et al\textsuperscript{71–73} have added to these studies with their findings that active (in contrast to passive) mobilization applies stress to the sutured tendon, enhances the strength of the repair and the biologic response, and obviates the loss of tensile strength during the first 3 weeks of healing. From these reports it has been clinically accepted that the most effective method of returning strength and excursion to repaired tendons involves the use of a strong, gap-resistant suture technique followed by the application of early post-repair controlled motion stress.

Adhesion Formation and Control

Factors that influence the formation of excursion-restricting adhesions around repaired flexor tendons include trauma to the tendon and sheath from the initial injury and the reparative surgery, tendon ischemia, tendon immobilization, gapping at the repair site, and excision of components of the tendon sheath. In 1964 Potenza\textsuperscript{111} described the quantitative formation of adhesions in proportion to the amount of tissue crushing and the number of surface injuries.
to the tendon, giving further support to the timehonored advice of Bunnell that a meticulous surgical technique must be used for flexor tendon surgery. Pennington and Amadio et al have shown that disruption of the vincula also has been associated with a decrease in the recovery of tendon excursion and Gelberman et al, Oei et al, Peterson and colleagues, Saldana et al, Tang and colleagues, Amiel et al, Frykman et al, Hagberg and Gerdin, Porat et al, Salti et al, and St Onge et al have provided studies and commentary regarding the pros and cons of repairing the tendon sheath.

Various biochemical agents have been studied in an attempt to modify adhesion formation around tendon repairs. Douglas et al and Lindsay and Walker studied the effect of antihistamines and the potential benefits of various steroid preparations was reported by Ketchum. Nonsteroidal anti-inflammatory drugs have been subject to the most recent laboratory investigations. Kulick and colleagues have provided laboratory and clinical evidence that ibuprofen was beneficial and Carstedt et al and Szabo and Younger have demonstrated the possibility of improving tendon excursion by blocking prostaglandin synthesis through the inhibition of the enzyme cyclooxygenase at the cell level. Peacock et al attempted to create controlled lathyrism with oral or topically applied beta-aminopropionitrile with varying degrees of success. Amiel et al, Frykman et al, Hagberg and Gerdin, Porat et al, Salti et al, and St Onge et al have evaluated various forms of hyaluronate (sodium hyaluronate or hyaluronic acid), topically enriched collagen solutions, and fibrin sealants;
while some of these compounds have demonstrated laboratory or clinical usefulness, none have found their way into widespread clinical usage. Efforts to mechanically block adhesion connections to repaired flexor tendons also have been described. The fact that none of these methods have made their way into recognized hand surgery publications testifies to their usefulness.

**Flexor Tendon Repair**

**Considerations**

In recent years there have been a large number of published reports that describe new and allegedly better methods of flexor tendon repair and post-repair motion protocols. These investigations stem from the consensus that the greater the increments of repair site stress and tendon excursion, the quicker the tendon will achieve normal tensile strength with fewer motion-restricting adhesions. Interpreting these reports and comparing them with other studies is difficult because they use different laboratory models, *in vivo* versus *in vitro* investigations, different testing methods, and diverse definitions of failure. Nevertheless, there have been major advances in the strength and gap resistance of tendon suture techniques, permitting more vigorous post-repair motion protocols and a global improvement in results.

Armed with substantial advances in the basic science of flexor tendons and the results of studies evaluating different methods of tendon suture and rehabilitation, many widely held concepts have been clinically abandoned. Primary repair of flexor tendons severed in the digital sheath has universally replaced the “no man’s land” concept, which favored secondary grafting. The concept that flexor tendon repair should be considered a surgical emergency also has been effectively dispelled by studies by Arons, Gainor, Green and Niebauer, Honner, Madsen, Matev et al, Salvi, Schneider et al, among others, which demonstrate that equal or better results usually can be achieved by delayed primary flexor tendon suture. Bolton, Brown, Fetrow, Jensen and Weilby, Kleinert et al, Strickland, and others also have effectively shown that it is better to repair both the FDP and FDS tendons rather than the FDP alone, as once was thought to be the wiser option. Flexor digitorum profundus advancement, which was once advocated for distal zone I injuries, has now been largely discarded in favor of direct suture, which better maintains the normal digital balance of the injured and adjacent digits.

**Flexor Tendon Retrieval**

An appreciation for the need to protect the delicate synovial lining of the flexor tendon sheath and the potential for motion-restricting adhesions to be propagated by repeated efforts to retrieve a retracted tendon end has given rise to several creative methods of facilitating tendon capture and repositioning. Kleinert et al recommended proximal-to-distal milking of the tendons toward the repair site and Rice and Yanni described the use of a reversed Esmarch tourniquet technique. Morris and Martin used skin hooks passed down the sheath to engage the tendon stumps, while Pennington used a suction catheter. The use of various catheters and silicone rods has been described by Kilgore et al, Sourmelis and McGrouther, and Titley.

**Flexor Tendon Suture Techniques**

**Core sutures.** Strickland listed the characteristics of an ideal primary flexor tendon repair:

- Sutures easily placed in the tendon
- Secure suture knots
- Smooth juncture of tendon ends
- Minimal gapping at the repair site
- Minimal interference with tendon vascularity
- Sufficient strength throughout healing to permit the application of early motion stress to the tendon

Published investigations of the characteristics and performance of differing flexor tendon repairs have added greatly to our understanding of the best way to suture a tendon in preparation for the application of motion stress. Urbaniak et al, Komanduri et al, Savage and Risitano, Silfverskiöld and Andersson, Shaieb and Singer, and Strickland have shown that the strength of a flexor tendon repair is roughly proportional to the number of suture strands that cross the repair site. Trail et al demonstrated that flexor tendon repairs usually rupture at the suture knots. Mashadi and Amis studied the effect of locking loops on repair strength and concluded that they contributed modestly to strength but could collapse and lead to gapping at moderate loads. Hatanaka and Manske studied the effect of the cross-sectional area of locking loops and concluded that an increase of 10% to 50% resulted in a proportionate increase in the ultimate tensile...
strength of the repair. Hotokezaka and Manske\textsuperscript{175} observed that the locking loop suture configuration tightened around tendon fibers and increased tensile strength compared with grasping loops, which pulled through tendon fibers when tensile forces were applied. Increasing the number of grasping loops increased the propensity for tendon gapping. Taras\textsuperscript{176} confirmed that larger-caliber sutures significantly increase repair strength.

Ketchum et al\textsuperscript{177,178} found that a polyfilament-ensheathed by caprolactan (Supramid, S. Jackson, Inc, Alexandria, VA) was the best tendon suture material; this is currently one of only a few sutures that are available with 2 strands per needle. Absorbable sutures have been developed for tendon repair and seem advantageous because of low long-term foreign body tissue reaction and reduction of stress shielding effects of the host tissue. Unfortunately, the optimal rates of material absorption and strength reduction are yet to be determined. Trail et al\textsuperscript{171} suggested that 3–0 or 4–0 braided sutures were clinically practical for flexor tendon repair because of their ease of placement, adequate strength, and minimum extension at time of failure.

Aoki et al\textsuperscript{179} and Pruitt et al\textsuperscript{180} indicated that the fewer the suture knots located in the tendon junction site the better, and that whenever possible it was best to locate knots outside the repair despite the potential for increased frictional drag on the tendon. Soejima et al,\textsuperscript{181} Komanduri et al,\textsuperscript{162} and Aoki et al\textsuperscript{172} have also convincingly showed that there are significant strength and biomechanical advantages to dorsal rather than palmar placement of core sutures. Finally, Trail et al\textsuperscript{172} have pointed out the importance of having equal tension across all suture strands to prevent differential loading and a consequent weakening of the repair.

The observation that the number of suture strands crossing the repair strongly influences the strength of the repair has initiated a departure from the 2-strand core sutures that were clinically dominant until the last 10 years. A number of 4-strand, 6-strand, and core sutures that were clinically dominant until the repair has initiated a departure from the 2-strand crossing the repair strongly influences the strength of the repair.

Preventing differential loading and a consequent weakening of the repair is one of the key goals of modern tendon repair. A number of studies have shown that differential loading can significantly reduce the strength of the repair. Trail et al\textsuperscript{172} have pointed out the importance of having equal tension across all suture strands to prevent differential loading and a consequent weakening of the repair.

Based on data from a number of studies and adjusting for friction, edema, and the effect of early repair stress, Strickland\textsuperscript{160,165} created rough esti-
mates and working numbers that allow the preparation of a reasonable strength versus force graph (Fig. 8). The safety of any 4-strand core suture combined with a running lock or horizontal mattress circumferential suture can be appreciated and should permit light composite grip during the entire healing period.

Sheath Repair

In recent years many surgeons have advocated repair of the flexor tendon sheath after tendon suture. Gelberman et al.,105 Lister,113,213,214 Peterson et al.,116,215 Saldana et al.,118 Tang and colleagues,119,120,216 and Tonkin and Lister121 studied the advantages and disadvantages to sheath repair; their cumulative work fails to give the clinician clear direction. The advantages of sheath repair are that it serves as a barrier to the formation of extrinsic adhesions, provides a quicker return of synovial nutrition, acts as a mold for the remodeling tendon, and results in better tendon–sheath biomechanics. The disadvantages to sheath repair are that it is

Figure 6. Techniques for end-to-end flexor tendon repair.
often technically difficult and that the repaired sheath may narrow and restrict tendon gliding. These studies also provide conflicting laboratory and clinical information regarding the biologic and biomechanical benefits of sheath repair. No clear-cut benefit has been established.

A number of autogenous and synthetic materials have been used to restore tendon sheath continuity. Deffino et al.\textsuperscript{217} Doyle,\textsuperscript{12} Kleinert and Bennett,\textsuperscript{218} Okutsu et al.,\textsuperscript{219} and Strickland\textsuperscript{220} preferred tendon grafts. Kessler et al\textsuperscript{221} and Liu and Lu\textsuperscript{222} used fascia and Lister\textsuperscript{213} used extensor retinaculum. Oei et al\textsuperscript{115} restored the synovial–cruciate sheath with peritenon while Eiken et al\textsuperscript{223} used tendon sheath; Dunlap et al\textsuperscript{224} and Hanff and Abrahamsson\textsuperscript{225} demonstrated that polytetrafluoroethylene worked well in the laboratory setting. Nishida et al\textsuperscript{226} reported that of all the sheath restoration methods they studied, extensor retinaculum creates the least resistance to tendon gliding.

Partial Tendon Lacerations

Wray et al\textsuperscript{227,228} created considerable controversy by recommending that partial flexor tendon lacerations should not be repaired. After those reports considerable debate ensued regarding the appropriate management of partial tendon lacerations. Chow and Yu,\textsuperscript{229} Bishop et al.,\textsuperscript{230} and McGeorge and Stilwell\textsuperscript{231} demonstrated that partial lacerations of 50% or less do not need to be sutured but that those greater than

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Peripheral (epitendinous) tendon suture techniques.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{A strength-versus-force graph showing 2-, 4-, and 6-strand repairs plotted against passive, light active flexion and strong grip. The data are adjusted for friction, edema, and stress.}
\end{figure}
50% should be repaired. Grewal et al\textsuperscript{232} recently confirmed that nonrepaired partial lacerations had a significantly higher ultimate load and stiffness than those that were repaired. The possibility of entrapment, rupture, and triggering of unrepaired partial severances also has been reported by Schlenker et al.\textsuperscript{233}

Post-Flexor Tendon Repair Rehabilitation

Rationale for Early Post-Repair Motion Stress

The traditional immobilization of repaired flexor tendons for 3 or more weeks has been almost universally abandoned. Recent hand surgery literature is replete with laboratory confirmation of the beneficial effects of applying early controlled forces to healing tissues, and descriptions of an assortment of post-tendon repair motion protocols speak to the clinical use of this biologic knowledge. Buckwalter,\textsuperscript{234} Evans and Thompson,\textsuperscript{68} Feehan and Beauchene,\textsuperscript{235} Gelberman and colleagues,\textsuperscript{105–109,236} Mass et al,\textsuperscript{237} Pruitt and colleagues,\textsuperscript{198,199} Tanaka et al,\textsuperscript{238} Woo et al,\textsuperscript{239} Wray et al,\textsuperscript{240} Kubota et al,\textsuperscript{241} and Aoki et al,\textsuperscript{71} in particular, have provided biologic verification that imparting early post-repair motion stress to repaired flexor tendon repairs provides a more rapid recovery of tensile strength, less adhesions, improved tendon excursion, and less repair site deformation.

Brown and McGrouther,\textsuperscript{242} Gelberman et al,\textsuperscript{105} Greenwald et al,\textsuperscript{69} Hagberg and Selvik,\textsuperscript{243} Hori be et al,\textsuperscript{59} and McGrouther and Ahmed\textsuperscript{60} conducted studies in an effort to determine the normal amount of flexor tendon excursion resulting from increments of digital joint motion, the gliding of repaired tendons, and the amount of excursion that may occur in the various post-tendon repair splints that are commonly used. It has been observed that passive metacarpophalangeal joint movement produces no relative motion of the flexor tendons. Distal interphalangeal joint motion produces excursion of the FDP of 1 to 2 mm per 10° of joint flexion while each 10° of proximal interphalangeal joint flexion results in excursion of both the FDP and the FDS of approximately 1.5 mm. Silfverskiöld et al,\textsuperscript{244} who measured the excursion of marked flexor tendon repairs, demonstrated that there is a substantial decrease in the normal movement of the profundus to an average of 0.3 mm per 10° of distal interphalangeal flexion (36%) while proximal interphalangeal motion retained approximately 1.3 mm (90%) of FDS and FDP excursion per 10° flexion.

The amount of tendon excursion that should occur for uninjured tendons in the original Kleinert-type splint, modifications of the Kleinert splint with a palmar bar pulley (Brooke Army Splint), and an experimental synergistic dynamic tenodesis splint that permits wrist extension (Mayo Clinic) have also been studied by Cooney et al,\textsuperscript{245} who demonstrated that improved excursion can be expected from the use of a palmar bar and that even greater excursion can be expected if wrist extension is added (Fig. 9). Differential excursion between the 2 digital flexors was also increased dramatically by the synergistic splint. Savage\textsuperscript{246} also has shown that a position of wrist extension and metacarpophalangeal joint flexion produces the least tension on a repaired flexor tendon during active digital flexion.

Early Motion Stress Post-Rehabilitation Programs

Following flexor tendon repair in zones I or II, there are several options for the application of motion stress to the repaired tendon to facilitate healing and maximize gliding. The once widely used rubber band technique popularized by Kleinert and colleagues\textsuperscript{151,153,247,248} and Lister et al\textsuperscript{7} in the 1960s, 1970s, and early 1980s has largely given way to modifications of that method and to passive and active motion protocols. McGrouther and Ahmed\textsuperscript{60}
and Phillips et al\textsuperscript{249} concluded that the original Kleinert splint was a poor mobilizer of the distal interphalangeal joint and that cross-union between the tendons should be expected to be a problem. In recent years modifications of the original Kleinert method have been tendered by Becker and Hardy,\textsuperscript{250} J. A. Chow et al,\textsuperscript{251} S. P. Chow et al,\textsuperscript{252} Citron and Forster,\textsuperscript{253} Edinburg et al,\textsuperscript{254} Knight,\textsuperscript{255} Reis,\textsuperscript{256} Slattery and McGrouther,\textsuperscript{257,258} and Werntz et al.\textsuperscript{259} These splints have used a variety of changes designed to create more complete composite digital flexion.

The controlled passive motion method originally recommended by Duran and Houser\textsuperscript{260} was shown to outperform immobilized flexor repairs by Strickland and Glogovac,\textsuperscript{8} and a retrospective study by Stone et al\textsuperscript{261} demonstrated that early passive motion was associated with improved total active motion for isolated FDP injuries. Proponents of the controlled passive motion protocols contend that it is less likely to result in flexion contractures than the rubber band flexion/active extension method and that the involved digit may be better protected between periods of exercise. Despite the enthusiasm for these and other passive tendon repair mobilization programs, Manske\textsuperscript{41} has expressed skepticism as to how much movement is actually realized at the repair site in the absence of muscle contraction to mobilize the tendon, particularly during the 1- to 3-week post-repair period. Additionally, Gault\textsuperscript{262} reported a series of repairs managed by a passive motion protocol that had less than ideal results.

Although Peck et al\textsuperscript{263} indicated that there may be little difference between the results of active and passive mobilization of flexor tendon repairs, there has been a growing trend toward the use of some increment of active digital motion in an attempt to obtain better functional recovery after flexor tendon repair. It has been demonstrated that 4- and 6-strand flexor tendon repair methods combined with strong circumferential sutures should be sufficiently strong to withstand light active forces throughout the healing period (see Fig. 8). While post-repair motion protocols vary somewhat, many follow the sequence recommended by Strickland\textsuperscript{167-170} in which the wrist is immobilized in modest flexion, the metacarpophalangeal joints in near full flexion, and the interphalangeal joints in extension when the hand is at rest. The motion program is initiated by passively flexing the injured finger, after which the wrist is extended and the patient is asked to actively maintain the flexed position of the digit (Fig. 10). Advocates of controlled active digital motion believe that this technique generates greater gliding of the healing tendon, less adhesions, and the ability to more rapidly achieve tendon strength than passive motion protocols.

In 1979 Becker et al\textsuperscript{264} reported the results of early active motion following the use of a strong beveled technique of tendon repair. Subsequent active motion protocols and the results of the clinical use of those programs have been described by Chow et al,\textsuperscript{251,265} Cullen et al,\textsuperscript{266} Elliot et al,\textsuperscript{267} Gratton,\textsuperscript{268} Lee,\textsuperscript{183} Sandow and McMahon,\textsuperscript{189} Savage and Risitano,\textsuperscript{164} Schenck and Lenhart,\textsuperscript{269} Silfverskiöld et al,\textsuperscript{201,204} Small et al,\textsuperscript{270} Strickland,\textsuperscript{167,169} and Taras et al.\textsuperscript{271} Several of these programs have used a strong 4-strand repair or its equivalent with a running lock loop, horizontal mattress, or intrafiber circumferential repair combined with early protected passive and active motion. The results are clearly better than with previous, more conservative techniques. It is interesting that the results of the use of early post-repair active motion have shown that the rupture rates are no greater than those for passive motion regimens.

**Late Restoration of Flexor Tendon Function**

Conventional free-tendon grafting after flexor division in a digit remains one of the most eloquent procedures in the hand surgeon’s armamentarium. The best descriptions of the techniques are found in the writings of Bunnell, Pulvertaft, Boyes, and Littler. While few advances in tendon grafting have occurred in recent years, Boyes and Stark,\textsuperscript{272} McClinton et al,\textsuperscript{273} and Stark et al\textsuperscript{274} have reported notable reviews of large clinical series and that good results have been obtained by grafting through an intact FDS for isolated FDP loss.

Tenolysis of adherent flexor tendon repairs or grafts remains an excellent salvage procedure in appropriate circumstances. Recent technical descriptions, rehabilitation methods, and results analyses by Baker et al,\textsuperscript{275} Fetrow,\textsuperscript{276} Foucher et al,\textsuperscript{277} Hunter et al,\textsuperscript{278} McCarthy et al,\textsuperscript{279} Schneider,\textsuperscript{280} Strickland,\textsuperscript{281} and Whitaker et al\textsuperscript{282} have contributed to previous information regarding this subject.

In the last 4 decades there have been significant advances in the ability to restore flexor tendon function to badly scarred digits. Staged reconstruction uses passive or active tendon implants, followed secondarily by a replacement graft. The implant and method that currently enjoy the most popularity have
largely resulted from the work of Hunter and colleagues; subsequent investigators have reported results using this method. Hunter et al. also pursued the development and clinical use of a permanent tendon implant; in some instances, the results of the use of these prostheses have been encouraging. Asencio et al. have demonstrated reasonable results from the use of human composite flexor tendon allografts for difficult salvage situations.

**Flexor Digitorum Profundus Avulsion**

The clinical presentation, pathomechanics, classification, and treatment of avulsion injuries of the FDP have been reported in the recent hand surgery literature. In particular, the reports of Leddy and colleagues, and Manske and Lesker have been helpful to our understanding of the condition. Figure 11 depicts the classification of profundus avulsions provided by Leddy and Packer.

**Evaluating the Results of Flexor Tendon Repair**

Students of flexor tendon surgery have been historically frustrated by the many variations in the methods of measurement and classification of the results reported in the literature. In recent years, the historic method of measuring the distance between the pulp of the distal phalanx and the distal palmar skin crease has been replaced by more scientifically reliable and comparable methods that measure the angular motion of the digital joints adjusted for any extension deficit. A critical analysis of 5 methods of evaluating the results of flexor tendon repair by So et al. concluded that the method of Buck-Gramcko et al. was the most reliable. A simpler system devised by Strickland and Glogovac that uses the combined flexion of the proximal and distal interphalangeal joints (while making a full composite fist) minus the extensor lag has enjoyed the most popularity in recent reports, probably because of its simplicity. The
results, expressed as a percentage of normal, can then be classified by the system reported by Kleinert and Verdan. Similar systems for the evaluation of staged tendon reconstruction and tenolysis also have been described by Whitaker et al and Strickland.

In the last 30 years there has been a steady improvement in the reported results of flexor tendon surgery. Recovery of good or excellent function can now be expected in 80% or more of most strong tendon repair followed by early post-repair motion protocols. In a multivariate prospective analysis of factors affecting results after flexor tendon repair in zone II, Silfverskiold et al stated that a large part of the variance in all the outcomes was probably related to the psychological and biologic characteristics of the patient. Harris et al confirmed that impression when investigating the etiology of acute rupture of flexor repairs during early mobilization with their finding that “in approximately half of these patients, tendon rupture followed acts of stupidity.”

The amount of scientific and clinical information that has been published regarding injuries to the flexor tendon in recent decades probably exceeds the total of all previous reports and comprises a tremendous and highly meaningful body of work. It has unquestionably resulted in markedly improved results for the management of these conditions, and one can rest assured that an equally impressive body of new information and even better clinical results will occur in this new millennium.

Any review of the important scientific contributions to the overall understanding of flexor tendons during the last few decades immediately creates a profound appreciation for both the enormity and the quality of the publications of two investigators: Paul R. Manske and Richard H. Gelberman. With their associates, they have produced a tremendous body of meaningful work and the elegance of their experimental models, their dedication to scientific validity, the simplicity and clarity of their writings, and the clinical relevance of their laboratory studies are renowned throughout the hand surgery world. The spectrum and diversity of their investigations and the sheer volume of their combined publications are truly overwhelming. It is particularly impressive that these two colleagues have provided so much toward a strong scientific basis for flexor tendon surgery. Hand surgeons and patients worldwide owe them a great debt of appreciation.

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