Journal of Clinical Orthopaedics and Trauma 10 (2019) 853–861

Contents lists available at ScienceDirect

Journal of Clinical Orthopaedics and Trauma

journal homepage: www.elsevier.com/locate/jcot

Flexor tendon injuries

Hari Venkatramani, Vigneswaran Varadharajan, Praveen Bhardwaj, Aashish Vallurupalli, S. Raja Sabapathy

Plastic Surgery & Trauma Reconstructive Surgery, Ganga Hospitals, Coimbatore, India

ARTICLE INFO

Article history:
Received 8 March 2019
Received in revised form
9 August 2019
Accepted 9 August 2019
Available online 19 August 2019

Keywords:
Flexor zones of hand
Pulley system
Core sutures
Early passive mobilization

ABSTRACT

Flexor tendon injuries have constituted a large portion of the literature in hand surgery over many years. Yet many controversies remain and the techniques of surgery and therapy are still evolving. The anatomical and finer technical considerations involved in treating these injuries have been put forth and discussed in detail including the rehabilitation following the flexor tendon repair. The authors consider, recognition and mastery of these facts form the foundation for a successful flexor tendon repair. The trend is now towards multiple strand core sutures followed by early active mobilization. However, the rehabilitation process appears to be one of the major determinant of the success following a flexor tendon repair. Early mobilization is essential for all the flexor tendon repairs as it is proved to improve the quality of the repaired tendon. The art of achieving the harmony between a stronger repair and unhindered gliding of the repair site through the narrow flexor tendon sheath simultaneously can be mastered with practice added to the knowledge of the basic principles.

1. Introduction

Regaining satisfactory digital function after flexor tendon laceration and repair in the digit remains one of the most challenging problems in hand surgery. The inaugural issue of Hand Clinics was devoted to flexor tendon repair.[1] At least 135 full length articles have been published on this topic in the American & European volumes of the Journal of Hand Surgery in the last 5 years alone. Yet many controversies remain and the techniques of surgery and therapy are still evolving. A proper understanding of these injuries at the histological and biomechanical level is necessary to improve outcomes. Data regarding the incidence of flexor tendon injuries in an Indian context is lacking. A study from the USA estimates this incidence at about 14/100,000-person years,[2] while a study in a Finnish population puts the figure at 7/100,000-person years.[3] In a pediatric population (<16 years), 31 flexor tendon injuries were found out of a total of 391 hand injuries.[4] In the author's Centre (Ganga Hospital, Coimbatore) in the year 2014, out of the 3032 new Hand Surgery patients operated, 166 cases of flexor tendon injuries were treated, majority of which were a part of complex hand trauma with injury to multiple structures and fingers.

The first flexor tendon repair dates back to the 11th century, however the Galenian dogma, deterred the progress till the 17th century.[5] Haller, through his experimental works, dislodged the belief and paved way for the attainments in this field.[6] Mason and Allen were the first to recommend immediate post- operative restricted or protected motion rather than complete immobilization,[7] to obtain better functional results for this “baffling problem” as remarked by Bunnell.[8] Their works were endorsed in the future by the doyens of hand surgery.

2. Anatomy and biology of flexor tendons

2.1. Anatomy of flexor tendons

There are two flexor tendons for each digit- flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP).[9] In the palm, the FDS tendons are superficial to the FDP but at the level of the MCP joint, the FDS splits into two slips (chiasma of Camper), allowing the FDP to pass between them and then become superficial to the FDS.

2.2. Pulley system

There is a fibrous flexor sheath surrounding the tendon extending from the neck of the metacarpal to the base of the distal phalanx. At certain places, the sheath is thickened, called the pulleys. Based on their general appearance, the pulleys are called

E-mail address: drhariv@gmail.com (H. Venkatramani).

https://doi.org/10.1016/j.jcot.2019.08.005
0976-5662/

annular and *cruciate*. They are named A1 to A5 for the annular pulleys and C1 to C3 for the cruciate pulleys. They help in preventing the bowstringing of the flexor tendon while flexing the fingers and improves the efficiency of the action by changing the translational force generated by the muscles into rotational movement in the phalanges.

In the thumb, traditionally three pulleys have been described. They are the A1 pulley over the metacarpophalangeal joint, A2 pulley over the interphalangeal joint and an oblique pulley running across the proximal phalanx.[10] The oblique pulley is an extension of the adductor pollicis aponeurosis and is considered most important for FPL function.

2.3. Nutrition of tendons

Wherever the tendons are surrounded by the synovial sheath, they derive their nutrition from the synovial fluid which is bathing them. In addition, they have their own vascular network which reaches them in the digit through attachments called vincula.[11] Both the superficial and deep tendon have two vinculae each-one *longus* (long) and one *brevis* (short).

2.4. Tendon healing

The gliding interface of the tendon is the most important aspect of its healing. The coefficient of friction of a normal human flexor tendon in its sheath is similar to that of an articular cartilage. Tendons heal both by intrinsic and extrinsic healing mechanisms, accomplished through tenocytes and fibroblasts respectively. In the clinical setting, both modes of healing occur simultaneously.[11] Early mobilization is found to reduce adhesions and improve the quality of tendon healing by facilitating intrinsic healing and suppressing healing through extrinsic mechanism.

3. Zones of flexor tendons

Verdan described the zones of flexor tendons according to the regions in which they lie. Classically 5 zones have been described for the fingers. They are as follows (Fig. 1):

- Zone I: Distal to the insertion of the flexor digitorum superficialis tendon. Only the FDP is present here. Moiemen & Elliot[12] have further classified this zone into three subzones.
- Zone II: Within the flexor sheath extending from the insertion of the flexor digitorum superficialis tendon distally to the A1 pulley proximally. This zone contains both the FDS and the FDP within the narrow confines of the digital flexor sheath and has been subdivided by Tang into four subzones.[13]
- Zone III: From A1 pulley distally to distal edge of the flexor retinaculum proximally. The lumbricals arise from the FDP tendons in this zone.
- Zone IV: Within the carpal tunnel under the flexor retinaculum. All digital flexors, along with the median nerve, are in close proximity to each other here.
- Zone V: Proximal to the flexor retinaculum. This includes the muscle level injuries in the forearm as well. To tailor the management according to specific site, this zone has been subdivided further by Sabapathy and Elliot.[14]

4. Clinical features

Diagnosis of a flexor tendon injury is mostly clinical. Injury to any flexor tendon causes the corresponding finger to be out of cascade and assume a relatively extended position (Fig. 2). On passive wrist extension, the fingers must flex by tenodesis. Lack of flexion of any digit with this maneuver is an indication of flexor tendon injury. This wrist tenodesis test is useful in the unconscious or uncooperative patient. Partial injuries must always be kept in mind and specifically tested for. Pain on resisted flexion is a sign of partial injury. The digital nerves travel close to the tendon and could be injured along, and hence the sensation should be checked in all the patients with flexor tendon injuries.

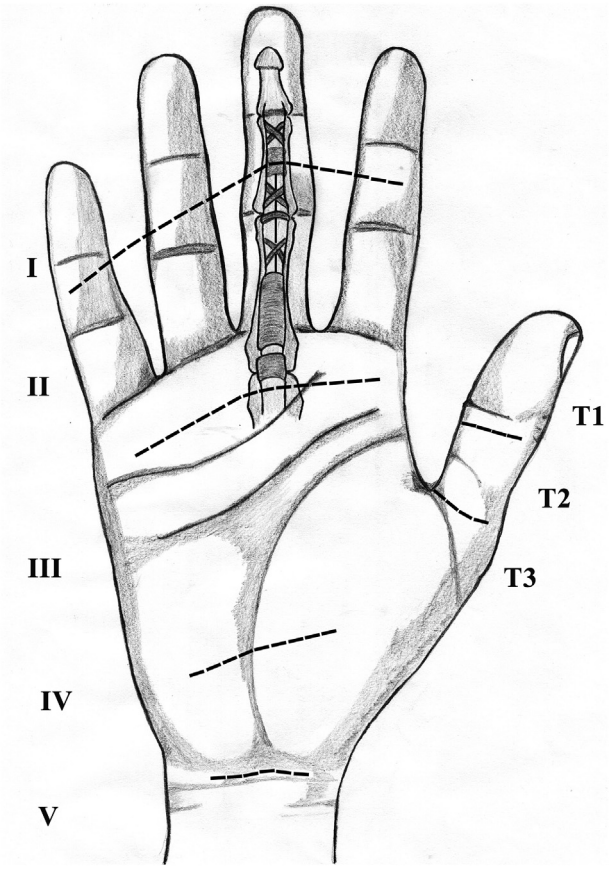

Fig. 1. Zones of the flexor tendon I–V (Thumb TI-TV).

5. Management

5.1. Suturing technique

Repairing a cut flexor tendon is not difficult, however, the

Fig. 2. A small laceration at the wrist level has resulted in loss of the flexion cascade of index finger- indicating injury to its flexor tendons- 'Finger tells the way'.

challenge lies in the fact that the tendon needs to be moved during the healing phase and it needs to glide through the confined flexor pulley system. Hence, the repair has to fine (not bulky) and at the same time strong enough to allow early mobilization. Early mobilization has been found to reduce adhesion formation and improve the quality of tendon healing.

Tang et al. in his review of the current surgical practice of the primary flexor tendon repair worldwide, found striking differences in the techniques practiced by various surgeons and units.[15] However, the two basic component of most of the suture techniques are core suture and the epitendinous suture. A core suture is passed through the substance of the tendon and grasps the substance of the tendon while traversing across it with the final knot being buried within the repair site or on the surface. An epitendinous suture is applied circumferentially around the tendon repair site. The core suture provides strength to the repair site and the number of core sutures passing across the repair site determines its strength.[16] The epitendinous suture makes the repair site smooth and also to a variable extent adds to the strength of the repair depending on the depth of the suture bite and suture configuration.[17]

Core sutures: One of the earliest and widely used core suture configurations were Kessler's and modified Kessler's suture. The modified Kessler has only one final knot in the core suture as opposed to the original Kessler suture. They had two strands of sutures running across the repair site with an added 'epitendinous' suture running all around the tendon smoothening the surface. These were good enough for passive mobilization but could not withstand the active mobilization regime which were proposed later to prevent adhesion formation and early restoration of function. More suture configurations have now been described which has increased the number of strands running across the repair site to four, six and eight or more.[18–21] These were found to have better strength and were able to withstand the increased forces generated during active mobilization. Table 1 shows the tensile force generated in the flexor tendon during various activities and Table 2 shows the tensile strength of the various suture configurations.[22] From these two tables, we can analyze that the type of repair greatly determines the type of rehabilitation program which could be followed after a repair. A two-strand repair only allows for passive mobilization protocols. Whereas, if an active mobilization protocol is opted for, a minimum of four strand repair is needed.

Fig. 3 shows the technique of applying a two strand and a four-strand suture (Fig. 3). A looped suture (Fig. 4) can provide two strands at the repair site by each passage across the repair site and hence minimize tendon trauma (Fig. 5). It is not yet available universally and has led to novel techniques to incorporate this configuration.[23] The concept of a looped suture in appealing. However, Calfee et al. found that a four-strand repair using single stranded 3-0 suture was significantly mechanically superior than the same four strand repair performed with the looped suture in a time-0 ex vivo human cadaver model.[24]

Suture Caliber: The size of the suture material used naturally would improve the strength of the repair but the tendon size would dictate the size of the suture to be used. In general, the flexor tendon repair could be repaired with a 3-0 or a 4-0 core suture and a 5-0 or 6-0 epitendinous suture. Studies have found that a 3-0 core suture is two to three times as strong as that of a 4-0 core suture.[25,26] However, interestingly Osei et al. found that the number of core sutures across the repair site was more determinant of the strength of the repair site rather than the size of the suture.[24] Comparing the strength of eight strand 4-0 suture with a four strand 3-0 suture, they found that the former was 43% stronger.[24] They concluded that although larger caliber suture has superior tensile properties, the number of core suture strands across the repair site has more effect on the strength of the repair at time-0. Hence, it was suggested that a surgeon should consider using suturing technique that prioritize multi-strand core suture repair

Table 1
Tensile stress on repaired tendon on various activities.

Activity	Stress in grams
Passive Motion	500 g
Light Grip	1500 g
Strong Grip	5000 g
Tip Pinch	9000 g

Table 2
Tensile strength of various core suture configurations with epitendinous suture. At one week the strength reduces to half of day-zero strength and it is 33% lesser at 3 weeks. With gradual tendon healing, the repair site becomes 20% stronger than the initial strength at 6 weeks.

Core Suture Configuration	0 Week	1 Week	3 Week	6 Week
		(-50%)	(-33%)	(+20%)
Two Strand	2500 g	1200 g	1700 g	2700 g
Four Strand	4300 g	2150 g	2800 g	5200 g
Six Strand	6000 g	3000 g	4000 g	7200 g

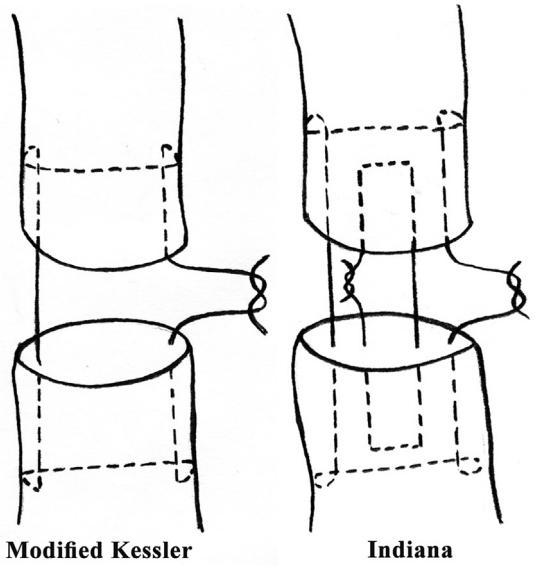

Fig. 3. Technique of applying a two-strand and a four-strand core suture in the flexor tendon.

Fig. 4. Looped suture – a needle has a loop of suture attached to it. Hence, providing a double suture across the repair site with a single passage.

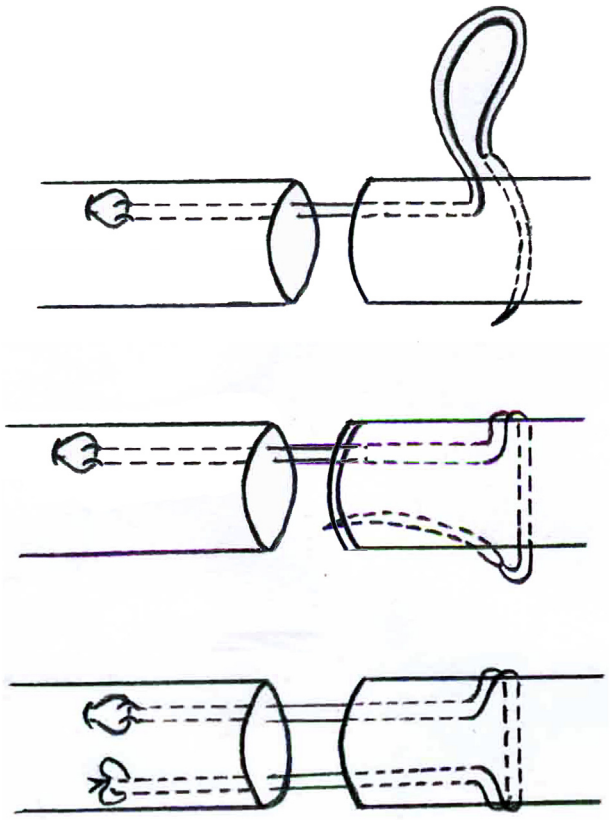

Fig. 5. Technique of introducing a four strand suture using a looped suture.

over an increase in suture caliber.[24]

Suture purchase: The purchase length of suture also has a bearing in the strength of the repair site. The minimum recommended length where the suture should exit from the cut end is 7 mm but 1 cm is considered optimal[27] (Fig. 6). Any length lesser than this will reduce the hold of the suture material and subsequently the strength of the repair. In all types of core sutures, it is also recommended to have the loops to be at least 2 mm in size.[27] This prevents tearing through of the loops that can lead to failure of repair. Applying a locking suture configuration to the core suture makes it even stronger.

Suture tension: Gap formation at the repair site is unacceptable and a gap of 3 mm or more could reduce the strength of the repair to the extent that it could rupture during post-operative mobilization. Tang has suggested that 10% extra tensioning of the repair site is helpful to resist gapping.[13] The tension can be achieved by using tighter core suture or efficient peripheral suture or both.

Suture material: The suture material should be non-absorbable. The two commonly used sutures are Prolene and Ethibond. Lawrence and Davis in their biomechanical analysis found both of these to have comparable tensile strength.[28]

Circumferential suture: The addition of a circumferential suture adds to the total strength of the repair, irrespective of the type of repair used.[29,30] While they were initially termed 'epitendinous', currently it is understood that deep bites produce better results. Also, more number of 'runs' around the repair is shown to be stronger. The depth of the bite and the configuration (locking) improves the strength provided by the epitendinous sutures.[31] The two commonly used configurations are shown in Fig. 7.

It is easier to first place the epitendinous suture in the posterior wall of the tendon, then apply the core suture and then complete the anterior epitendinous suture. This sequence of suturing does not require to flip the tendon around for repairing the posterior wall in the narrow space generally available while operating in this area. Also, it prevents over-tightening and bunching of the repair site. Fig. 8 describes the steps of the suturing technique.

5.2. Timing of flexor tendon repair

Primary tendon repair is defined as the repair done within 24 h from the time of injury; delayed primary repair is called so when it is done within 24 h to 10 days; repair done after 10 days is called as secondary repair and when it is done after 4 weeks it is called as late secondary repair.[32] Primary repair of flexor tendon is the standard practice. If suitable conditions or experienced surgeon is

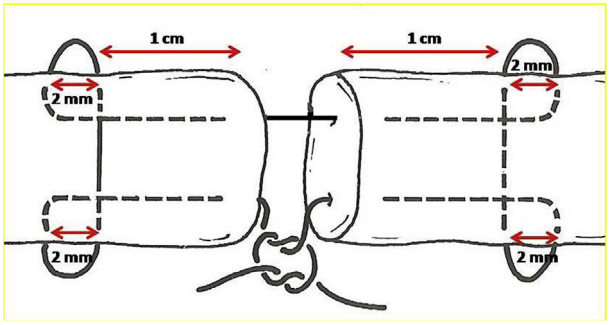

Fig. 6. The recommended dimensions while introducing a core suture in the injured flexor tendon. The core suture should exit at about 1 cm from the cut end and the loop of suture should have a tendon substance bite of about 2 mm to have a good hold on the tendon.

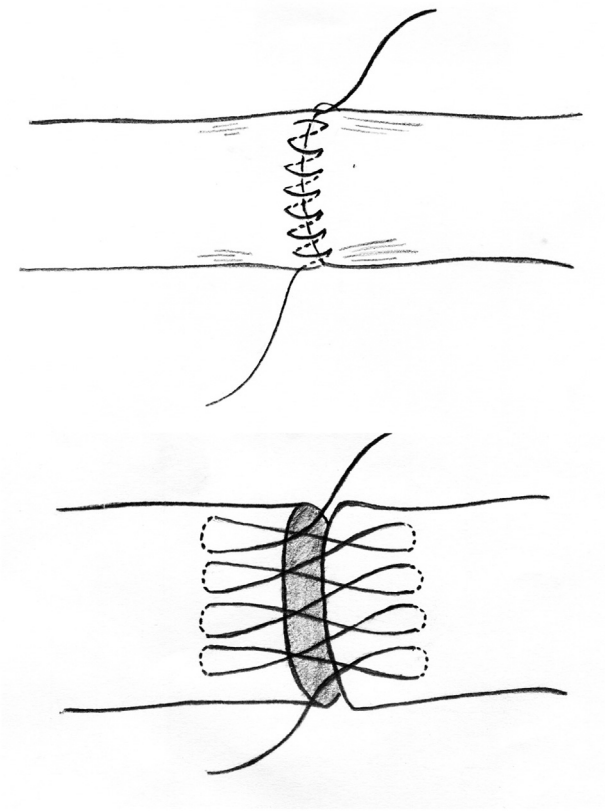

Fig. 7. Two commonly used techniques of circumferential sutures- simple running suture and crisscross locking sutures.

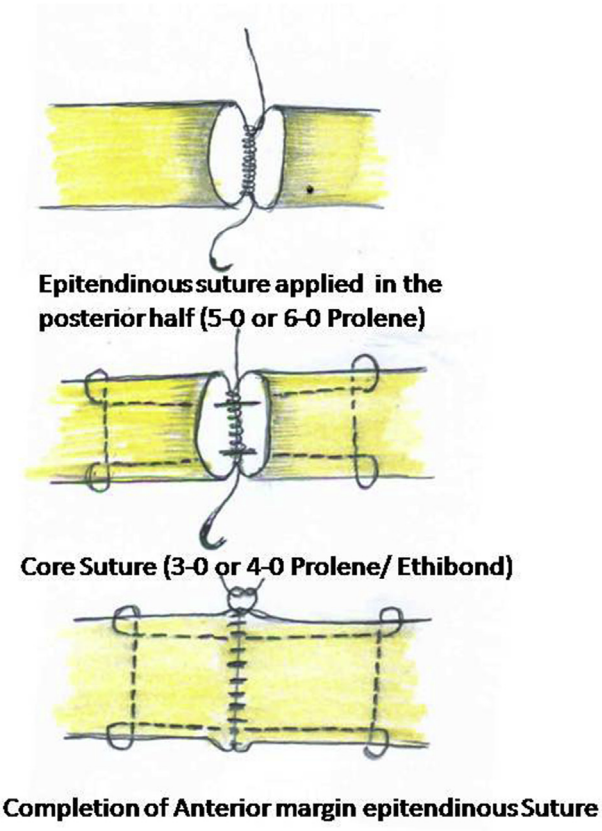

Fig. 8. To make the tendon repair easy, it is better to first place the epi-tendinous suture in the posterior half of the tendon, then put the core suture and after tying the core suture complete the anterior half epi-tendinous repair.

not available, flexor tendon surgery should not be considered as an emergency. Elliot et al. have shown that the repair done up to 72 h after the injury does not unduly affect the outcome of the flexor tendon repair.[33]

5.3. Extending the incision for flexor tendon repair

The incision for the flexor tendon repair should allow visualization of the cut ends and should provide enough space to repair the tendons. The laceration can be extended in a Brunner incision fashion or a mid-lateral exposure can be done (Fig. 9). If the injury has occurred in extended position of the finger, the cut ends would be very near to the laceration and extensive exposure is not required. More distal exposure is required if the flexor tendon injury has occurred in flexed position of the finger as the distal cut end would be away from the laceration site (Fig. 10). This could be known from the mechanism of injury. Intra-operatively one can just flex the finger fully and see if the distal cut end is popping out at the site of laceration, if not the cut end is much distal and more distal exposure is needed. If more distal exposure is needed, authors prefer a mid-lateral incision or else, a Brunner incision is used.

Fig. 9. Brunner criss-cross incision shown in the ring finger and mid-lateral exposures incision shown in the little finger. The incision should never cross the finger creases perpendicularly.

5.4. Retrieval of the proximal tendon end

The proximal tendon end, if not retracted too proximally, may be brought into the site of injury by flexing the wrist and by proximal-to-distal milking which helps in pushing it distally. If it cannot be achieved it can be grasped very gently using a fine hemostat and brought into the wound. This could be tried only once lest the tendon edges get ragged.

If any of these maneuvers fail, one should not hesitate to extend the incision proximally (Brunner zigzag fashion) to find the proximal end or make a separate incision just proximal to the A1 pulley in the palm. Once the proximal cut end is found the tendon end can be delivered to the injury site through the flexor sheath using a fine plastic tube or silicone catheter.[34]

5.5. Partial injury of the flexor tendons

If the injury involves less than 50% of the tendon substance there is no need to suture, rather the frayed cut ends could be trimmed and the surface made smooth.[11] Immediate active movement should be encouraged to avoid adhesions. Laceration involving more than 50% of the tendon should be repaired with a core suture and mobilized as per the flexor tendon mobilization protocol.

5.6. Management of pulleys during tendon repair

Any increase in the size of the flexor tendons either due to injury or edema or tendon repair can cause impediment in its proper gliding, especially in the area of compact pulley system like zone-2. Due to this problem, during the initial part of the century, repairs in these areas were avoided, giving them the eponymous name of “No man's zone”.

Even a properly executed tendon repair can give rise to some increase in the volume of the tendon and hence it can find resistance in gliding proximally or distally as the case may be. This problem can be addressed to a certain extent by opening a part or whole of the pulleys which is called venting of the pulleys.[35] A2 and A4 pulleys are considered to be functionally most important and effort should be made to preserve them. If exposure of the tendon or gliding of the repair site demands, a part of these pulleys can be excised or vented. Tomaino et al. in their biomechanical study found that 25% of the A2 pulley, up to 75% of the A4 and 25% of the A2 and A4 together can be excised without significant effects on angular rotation.[36]

After flexor tendon repair, the surgeon should move the finger and make sure that the repair site traverses comfortably without getting stuck into any of the pulleys. If the gliding is not smooth, venting of the pulleys should be done to allow free movement of the repair site.

5.7. Post-operative splinting

After the flexor tendon repair, a dorsal slab or splint is applied

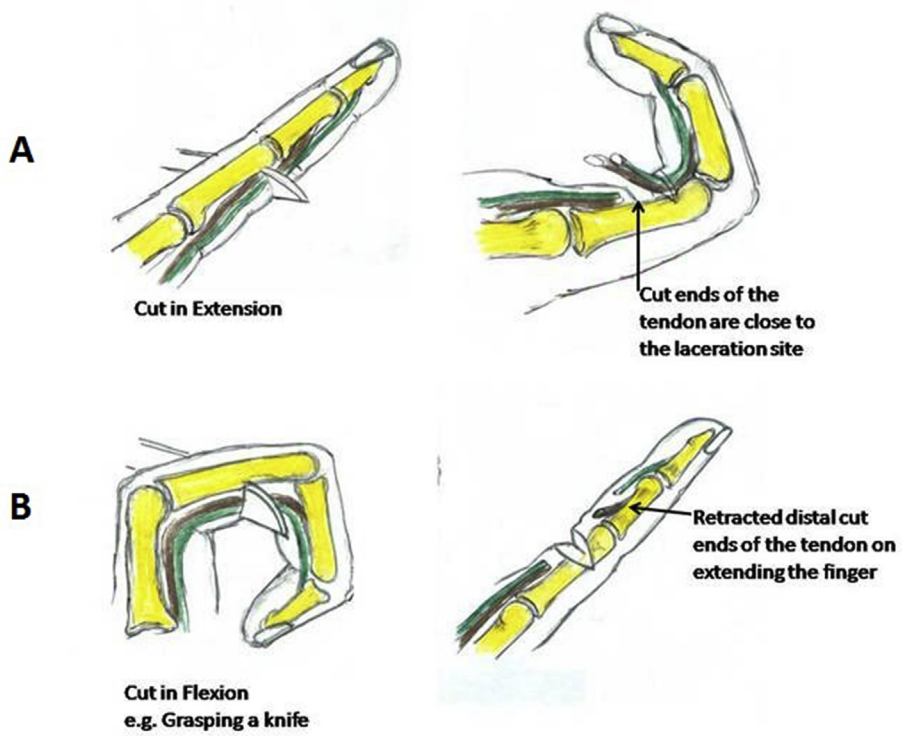

Fig. 10. Position of tendon cut ends with respect to the finger position at the time of injury. A- When the injury happens with finger in extension (assault) the distal cut end will be close to the site of laceration. B- When the injury happens with the fingers in flexion (as while grasping a knife) the distal cut end would be very distal when the finger is kept extended while operating. Flexion of the finger will bring the cut end to the site of laceration.

with the wrist flexed at 10–20° and the metacarpophalangeal joints flexed at around 70° and the slab extending beyond the finger tips. The interphalangeal joints are kept in a comfortable flexion position. The rationale behind this is to relax the tendons and avoid stretching at the repair site.

6. Rehabilitation after flexor tendon repair

An array of therapy regimens has been described and these protocols have been changing with time. The method, a given surgeon follows is based on his training and experience. Any flexor tendon repair travels through the following stages which might guide the mode of therapy to be adhered:

i. Early stage, the protective period when the tensile strength of the flexor tendon repair site is the weakest and lasts for 3–4 weeks
ii. Intermediate stage during which remodeling of the repaired tendons takes place and when stress to the tendon is increased either by starting mobilization or removing the splint.
iii. Late stage, which begins at 6–8 weeks when stress to the tendon is further increased and muscle strengthening and activities of daily living are started.

Basically, these protocols can be grouped into immobilization protocols where complete immobilization of the tendon repair site is done generally for 3–4 weeks, the early passive motion protocol (e.g. Kleinert protocol, Duran Houser protocol, Washington protocol),[37–39] where the repair site is passively mobilized at 48 h from surgery and the early active motion protocol (e.g. Gratton protocol, Strickland protocol, Allen protocol, Silverskiold& May protocol)[40–43] which can be utilized only when a stronger repair is done with a four or six strands core sutures. Starr et al. performed a systematic review of flexor tendon rehabilitation protocols in 2013, including flexor tendon injuries at all zones rehabilitated with early passive (including both Duran or Kleinert types) or early active mobilization protocols. They found that patients who underwent early passive mobilization protocol (1598 tendon repairs) had 4% ruptures (57 fingers) and 9% (149 fingers) had decreased range of movements.[44] Whereas, among the 1412 tendon repairs which were rehabilitated with early active mobilization protocol had 5% ruptures (75 fingers) and 6% (80 fingers) had decreased range of motion. This indicates that the early active mobilization patients had higher risk of rupture while the patients with passive mobilization protocols had more limitation of range of motion. They also observed that when the publications were chronologically analyzed there was statistically significant trend towards decrease in the rupture rates over time with both the methods of rehabilitation. They concluded that with modern improvements in suture materials and technique, early active mobilization may provide better motion while maintaining low rupture rates.

At the author's institution, the Duran Houser protocol is used with minimal modifications as follows. The patient is provided with a dorsal below elbow plaster support extending to the fingertips with the wrist in 20° flexion and metacarpophalangeal joints in relaxed position of flexion. Starting from the second postoperative day, passive flexion and active extension of individual interphalangeal joints are carried out till four weeks from surgery. At this time, the plaster support is converted into a thermoplastic splint, which has to be worn full time for 6 weeks from surgery. Active assisted flexion and active extension of the fingers are carried out between 4 and 6 weeks and active flexion and extension are allowed thereafter. The authors found gratifying results as shown

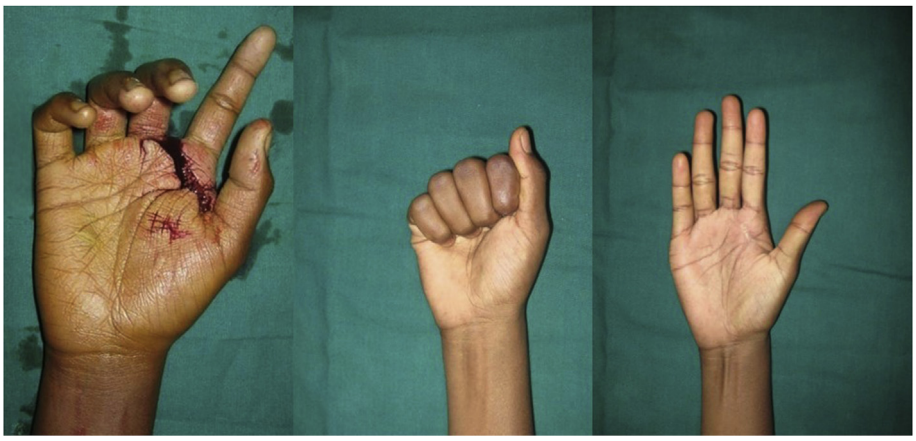

Fig. 11. Results of zone-II flexor tendon injury, treated with primary repair followed by early passive mobilization protocol.

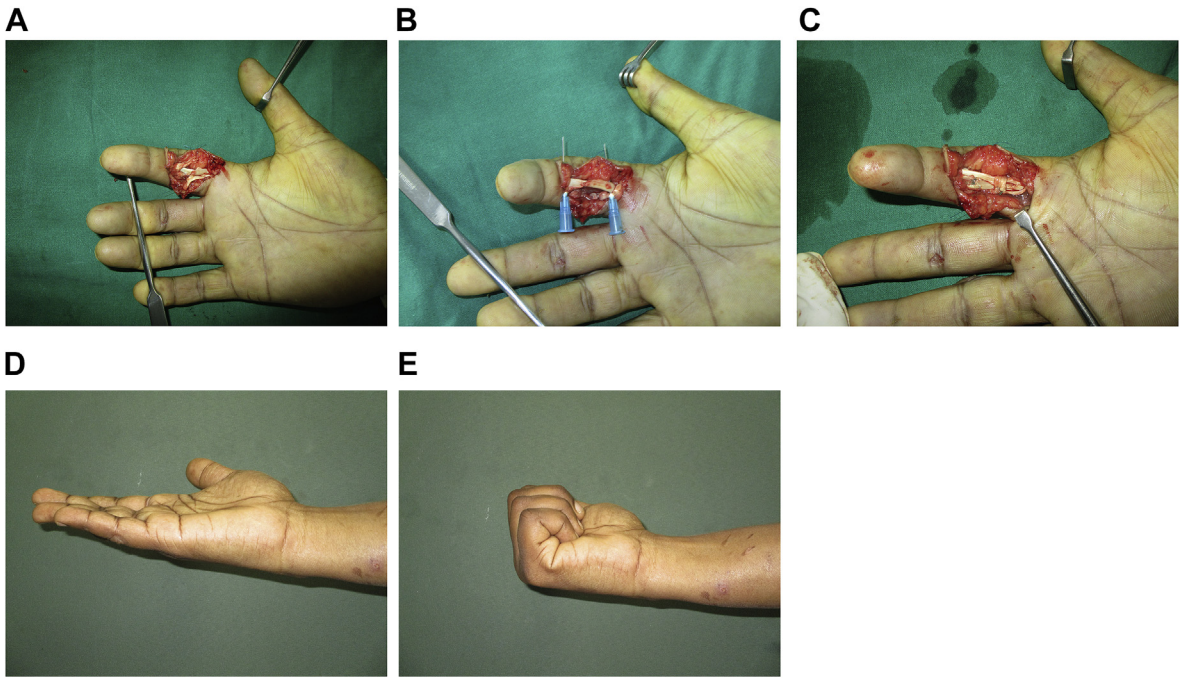

Fig. 12. a–e: Results of zone-II flexor tendon injury, treated with primary repair and pulley reconstruction.

with this protocol (Figs. 11 and 12).

7. Complications

Despite adhering to the above mentioned meticulous repair technique and rehabilitation protocol, flexor tendon repair is fraught with complications. The most disastrous of them being the rupture of the repaired tendons. The percentage of rupture in most of the series reported vary and they are less than 10%.[45–47] Most ruptures happen during the first two weeks of the repair as the repair site is weakest between 6 and 12 days.[48] Such events are usually noticed by the patient or the therapist, when they can feel the loss in the flexion power or the sudden 'popping'. In these cases, prompt exploration followed by the repair of the ruptured tendon is warranted.[11,49,50] The second common complication, tendon adhesions are part of the healing process and mainly result from extrinsic mode of healing. They cannot be totally avoided but can be minimized by atraumatic surgical technique, prevention of gaping at the repair site by making strong repair and instituting early mobilization protocol. The most typical clinical finding of tendon adhesion is limited active movement with full passive movement.Ultrasound imaging is very helpful in ascertaining the continuity of the flexor tendon.[51] Initial line of treatment in physiotherapy. Active pull-through exercise with the wrist in flexion should be instituted.[52] The therapy program is followed rigorously and the progress is monitored. If therapy fails tenolysis surgery is indicated. In general, it is indicated only after 3 months and preferably after 6 months as delay reduces the chances of tendon rupture during the tenolysis. Joint contractures, quadriga effect and lumbrical plus deformity are the other notable complications.

8. Secondary reconstruction of flexor tendons

In the unfortunate event of rupture of repaired tendon when the

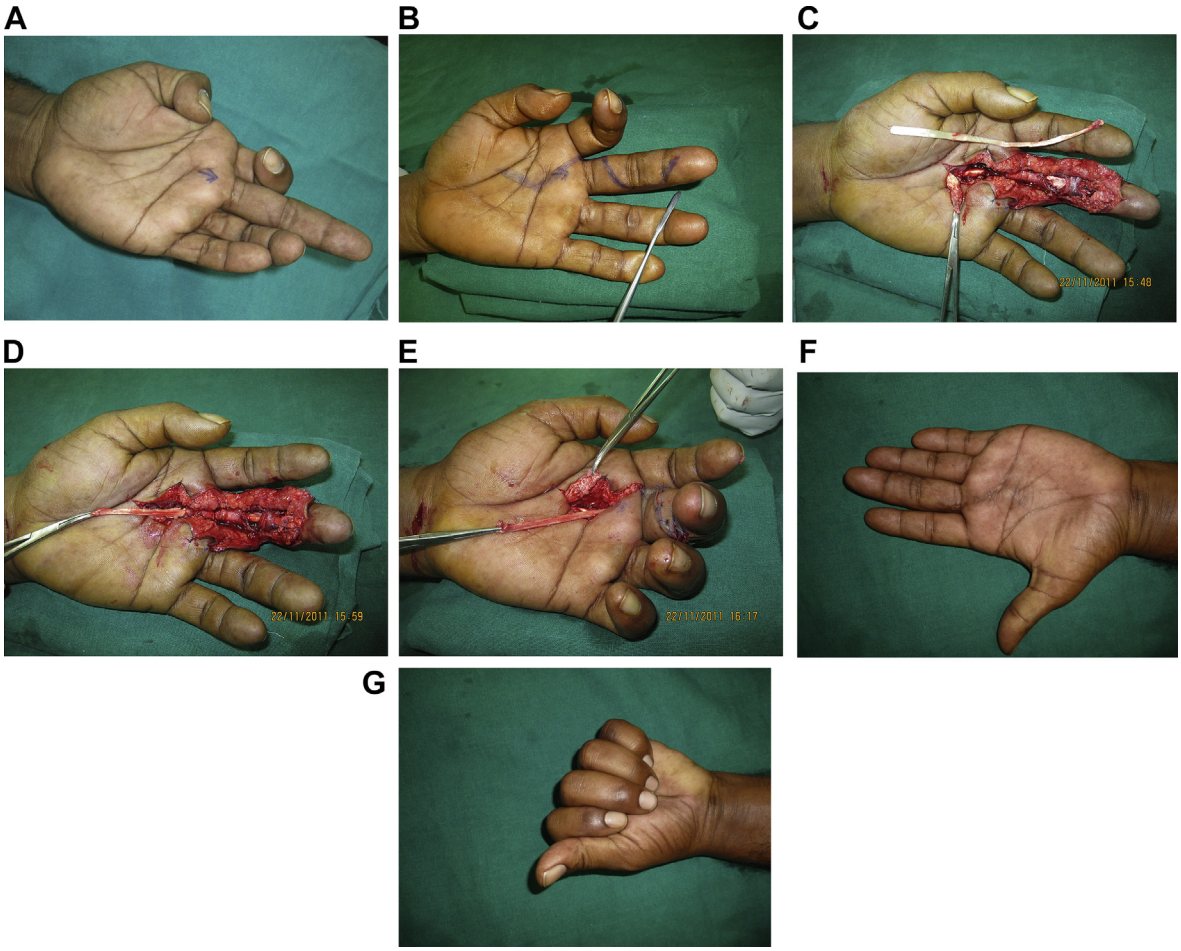

Fig. 13. a–g: Steps and results of single stage secondary flexor tendon reconstruction.

scarred ends measure more than 1 cm, delayed presentation or associated with segmental loss of flexor tendons, single stage or two staged flexor tendon reconstruction is required.[53,54] Choice between the two is directed by the overlying soft tissue cover and the pulley system. When the pulleys are intact but constricted or minimally scarred, one can proceed with the so called Balloon sheath flexorplasty where the pulleys and the fibrous flexor sheath are dilated (Fig. 13). When the pulleys are fibrosed or absent, two stage reconstruction is carried out. In this technique, a path for the flexor tendon to glide in, is created by placing a silastic (silicon) rod in the anatomical location of the flexor tendon and recreating the A2 and A4 pulley with tendon grafts. Silastic rod forms a good tubular pseudosheath around it which can act as a smooth covering for the tendon graft to be placed at second stage (Fig. 14). After the initial placement of the rod the patient undergoes aggressive physiotherapy to improve the range of the motion in the joints once the suture line heals.

In the second stage, the rod is replaced by a flexor tendon graft under the new pulley system. The technique involves exploration of the proximal end of the rod to which the distal end of the graft is sutured. The distal end of the rod is identified and pulled out, retrieving the tendon graft through the path created. The distal repair is completed and the wounds in the digits are closed before the proximal repair. The second stage of tendon insertion is done about 3–6 months later.[55]The donor tendons which can be used as graft include- flexor digitorum superficialis tendon from the same finger or palmaris longus or plantaris tendon. An intrasynovial tendon like FDS is thought to provide better gliding of the tendon and better outcome.[56] If multiple fingers are involved and the segmental gap length is more fascia lata can be used.

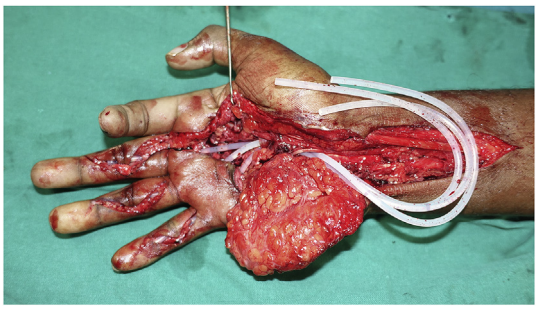

Fig. 14. Silastic rods placement for two staged secondary flexor tendon reconstruction.

Conflicts of interest

None to Declare.

References

1. Manske PR. History of flexor tendon repair. *Hand Clin*. 2005;21(2):123–127.
2. de Jong JP, Nguyen JT, Sonnema AJ, Nguyen EC, Amadio PC, Moran SL. The

incidence of acute traumatic tendon injuries in the hand and wrist: a 10-year population-based study. *Clin Orthop Surg*. 2014;6(2):196–202.
3. Manninen M, Karjalainen T, Määttä J, Flinkkilä T. Epidemiology of flexor tendon injuries of the hand in a Northern Finnish population. *Scand J Surg*. 2016;Aug: 1–5.
4. Jeon BJ, Lee JI, Roh SY, Kim JS, Lee DC, Lee KJ. Analysis of 344 hand injuries in a pediatric population. *Arch Plast Surg*. 2016;43(1):71–76.
5. Siegel RE. *Galen on Psychology, Psychopathology, and Function and Diseases of the Nervous System. An Analysis of His Doctrines, Observations and Experiments*. Basel: Karger; 1973.
6. Gratz CM. The history of tendon suture. *Med J Rec*. 1928;127:156–157 (213–5).
7. Mason ML, Allen HS. The rate of healing of tendons: an experimental study of tensile strength. *Ann Surg*. 1941;113:424.
8. Bunnell S. *Surgery of the Hand*. second ed. Philadelphia: JB Lippincott; 1948.
9. Sabapathy SR, Bhardwaj P. Tendon injuries. In: Sivananthan S, Sherry E, Warnke P, Miller MD, eds. *Mercer's Text Book of Orthopaedics and Trauma*. Hodder Arnold; 2012:1292–1301.
10. Zafonte B, Rendulic D, Szabo RM. Flexor pulley system: anatomy, injury, and management. *J Hand Surg Am*. 2014;39(12):2525–2532.
11. Strickland JW. Development of flexor tendon surgery: twenty-five years of progress. *J Hand Surg Am*. 2000;25(2):214–235.
12. Moiemen NS, Elliot D. Primary flexor tendon repair in zone 1. *J Hand Surg Br*. 2000;25(1):78–84.
13. Tang JB. Indications, methods, postoperative motion and outcome evaluation of primary flexor tendon repairs in Zone 2. *J Hand Surg Eur*. 2007;32(2):118–129.
14. Sabapathy SR, Elliot D. Complex injuries to the flexors in the hand and forearm. In Complex Injuries of the Hand Ed. Cheema TA, JP Medical Publishers, London.
15. Tang JB, Amadio PC, Boyer MI, et al. Current practice of primary flexor tendon repair. A global view. *Hand Clin*. 2013;29:179–189.
16. Savage R. In vitro studies of new method of flexor tendon repair. *J Hand Surg Br*. 1985;10:135–141.
17. Verdan CE. Primary repair of flexor tendons. *J Bone Joint Surg Am*. 1960;42: 647–657.
18. Tsuge K, Ikuta Y, Matsuishi Y. Repair of flexor tendons by intratendinous tendon suture. *J Hand Surg Am*. 1977;2:436–440.
19. Sandow MJ, McMohan M. Single-cross grasp six-strand repair for acute flexor tendon tenorrhaphy. *Atlas Hand Clin*. 1996;1:41–64.
20. Winters SC, Gelberman RH, Woo SL, et al. The effects of multiple strand suture methods on the strength and excursion of repaired intra synovial flexor tendons:a biomechnical study in dogs. *J Hand Surg Am*. 1998;23:97–104.
21. Silverskiold KL, Andersson CH. Two new methods of tendon repair: an in vitro evaluation of tensile strength and gap formation. *J Hand Surg Am*. 1993;18: 58–65.
22. Rekant MS. Acute laceration of flexor tendons. https://musculoskeletalkey.com/acute-laceartion-of-flexor-tendons/. Accessed June 17, 2017.
23. Wu YF, Cao Y, Zhou YL, et al. Bio-mechanical comparisons of four strand tendon repairs with double stranded sutures: effects of different locks and suture geometry. *J Hand Surg Eu*. 2011;36:476–484.
24. Osei DA, Stepan JG, Calfee RP, et al. The effect of suture caliber and number of core suture strands on zone II flexor tendon repair: a study in human cadaver. *J Hand Surg Am*. 2014;39:262–268.
25. Barrie KA, Tomak SL, Cholewicki J, et al. Effect of suture locking and suture caliber on fatigue strength of flexor tendon repairs. *J Hand Surg Am*. 2001;26: 340–346.
26. Uslu M, Isik C, Ozashin M, et al. Flexor tendon repair: effect of core sutures caliber with increased number of suture strands and peripheral sutures. A shhep model. *Orthop Traumatol Surg Res*. 2014;100:611–616.
27. Tang JB, Zhang Y, Cao Y, et al. Core suture purchase affects strength of tendon repair. *J Hand Surg Am*. 2005;30:1262–1266.
28. Lawrence TM, Davis TR. A biomechanical analysis of suture materials and their influence on a four-strand flexor tendon repair. *J Hand Surg*. 2005;30A: 836–841.
29. Boyer MI, Gelberman RH, Burns ME. Intra-synovial flexor tendon repair. An experimental study comparing low and high levels of in vivo force during rehabilitation in canines. *J Hand Surg Am*. 2009;83:891–899.
30. Dona E, Turner AW, Gianoutsos MP, et al. Biomechanical properties of four circumferential flexor tendon sutures techniques. *J Hand Surg Am*. 2003;28: 824–831.
31. Merrel GA, Wolfe SW, Kacena WJ, et al. The effect of increased peripheral suture purchase on the strength of flexor tendon repairs. *J Hand Surg Am*. 2003;28:464–468.
32. Cannon DL. Flexor and Extensor tendon injuries. In: Azar FM, Beaty JH, Canale ST, eds. *Campbell's Operative Orthopaedics*. thirteenth ed. Philadelphia: Elsevier; 2017:3360.
33. Elliot D. Secondary surgery of the flexor tendons. *Indian J Plast Surg*. 2005;38: 9–15.
34. Kamath JB, Bhardwaj P. A simple, semirigid, and surgeon friendly tendon retriever and flexor sheath dilator. *J Hand Surg Am*. 2007;32:269–273.
35. Elliot D. Primary flexor tendon repair: operative repair, pulley management and rehabilitation. *J Hand Surg Br*. 2002;27:507–513.
36. Tomaino M, Mitsionis G, Basitidas J, Grewal R, Pfaeffle J. The effect of partial excision of the A2 and A4 pulleys on the biomechanics of finger flexion. *J Hand Surg Br*. 1998;23(1):50–52.
37. Kleinert HE, Kutz JE, Ashbell TS, et al. Primary repair of lacerated flexor tendons in no man's land. Proceedings, American Society for Surgery of Hand. *J Bone Joint Surg Am*. 1967;49:577.
38. Duran RJ, Houser RG, et al. *Management of Flexor Tendon Lacerations in Zone II Using Controlled Passive Motion Post-operatively. Rehabilitation of Hand*. St. Louis: Mosby; 1978.
39. Dovelle S, et al. The Washington regimen: rehabilitation of the hand following flexor tendon injuries. *Phys Ther*. 1989;69:1034.
40. Gratton P. Early active mobilization after flexor tendon repair. *J Hand Ther*. 1993;6:285.
41. Strickland JW. Flexor tendon repair. Indiana method. *Indiana Hand Centre Newsl*. 1993;1(1).
42. Allen BN, et al. Ruptured flexor tendon tenorrhaphies in zone II: repair and rehabilitation. *J Hand Surg[Am]*. 1987;12:18.
43. Silverskiold KL, et al. Flexor tendon repair in zone II with a new suture technique and an early mobilization programme combining passive and active flexion. *J Hand Surg [Am]*. 1994;19:53.
44. Starr HM, Snoddy M, Hammond KE, Seiler 3rd JG. Flexor tendon repair rehabilitation protocols: a systematic review. *J Hand Surg*. 2013;38:1712–1717.
45. Small JO, Brennen MD, Colville J. Early active mobilisation following flexor tendon repair in zone 2. *J Hand Surg [Br]*. 1989;14(4):383–391.
46. Tang JB. Outcomes and evaluation of flexor tendon repair. *Hand Clin*. 2013;29(2):251–259.
47. Sirotakova M, Elliot D. Early active mobilization of primary repairs of the flexor pollicis longus tendon with two Kessler two-strand core sutures and a strengthened circumferential suture. *J Hand Surg [Br]*. 2004;29(6):531–535.
48. Taras JS, Gray RM, Culp RW. Complications of flexor tendon injuries. *Hand Clin*. 1994;10(1):93–109.
49. Harris SB, Harris D, Foster AJ, Elliot D. The aetiology of acute rupture of flexor tendons repair in zone II: a multivariate prospective analysis. *J Hand Surg [Br]*. 1993;1:167–179.
50. Leddy JP. Flexor tendons: acute injuries. In: Green DP, ed. *Operative Hand Surgery*. New York, NY: Churchill Livingstone; 1982:1359.
51. Jeyapalan K, Bisson MA, Dias JJ, Griffin Y, Bhatt R. The role of ultrasound in the management of flexor tendon injuries. *J Hand Surg Eur*. 2008;33(4):430–434.
52. Messer TM, Kleinert HE. Complications of flexor tendon injuries and their management. In: Venkataswami R, ed. *Surgery of the Injured Hand: Towards Functional Restoration. New Delhi Jaypee*. 2009:254.
53. Boyes JH. Flexor-tendon grafts in the fingers and thumb; an evaluation of end results. *J Bone Joint Surg Am*. 1950;32A(3):489–499.
54. Schneider LH. Staged tendon reconstruction. *Hand Clin*. 1985;1(1):109–120.
55. Battiston B, Triolo PF, Bernardi A, Artiaco S, Tos P. Secondary repair of flexor tendon injuries. *Injury*. 2013;44(3):340–345.
56. Pike JM, Gelberman RH. Zone II combined flexor digitorum superficialis and flexor digitorum profundus repair distal to the A2 pulley. *J Hand Surg Am*. 2010;35(9):1523–1527.