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J Hand Surg Eur Vol 2014 39: 6 originally published online 21 June 2013
DOI: 10.1177/1753193413492914

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JHS(E)

The Journal of Hand Surgery
(European Volume)
2014, Vol 39E(1) 6–19
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Recent developments in flexor tendon repair techniques and factors influencing strength of the tendon repair

Y. F. Wu and J. B. Tang

Abstract

Over the last decade, both basic researchers and surgeons have sought to identify the most appropriate techniques to be applied in flexor tendon repairs. Recent developments in experimental tendon repairs and clinical outcomes of newer repair techniques have been reviewed in an attempt to comprehensively summarize the most critical mechanical factors affecting the performance of tendon repairs and the surgical factors influencing clinical outcomes. Among them, attention to annular pulleys, the purchase and tension of the core suture, and the direction and curvature of the path of tendon motion have been found to be determining factors in the results of tendon repair.

Keywords

Tendon repair technique, repair strength, influencing factors

Date received: 7th June 2012; revised 31th October 2012; accepted 14th December 2012

Newer methods of tendon repair

Improving the strength of repaired tendons has long been a goal of hand surgeons. Basic researchers and surgeons have been striving to prevent disruption of surgically repaired tendons. To achieve this goal, the repair methods must be strong enough to withstand the gliding forces and resistance during postoperative mobilization. An ideal repair should provide adequate strength to prevent gap formation and failure of the repair, while causing minimal tendon damage and tissue reaction. This article reviews the development of newer tendon repair methods in both biomechanical studies and clinical applications over the past decade and analyses the major factors that have been shown to be important when repairing flexor tendons in the hand. In the last decade, we have seen a major change in suturing technique: the development and widespread use of multi-strand repair methods. Almost all newly developed techniques in this period are strong multi-strand repairs, and clinical reports have been centred on the application or clinical outcomes of these methods. These repairs are now used by most surgeons and represent a major development in tendon surgery over the past decade.

Methods developed in biomechanical studies

The 4- or 6-strand repairs were developed in the 1980s and 1990s, but in the first decade of this century, we saw a simplification of some of these methods (see Figure 1 and Table 1 for a summarized comparison of these biomechanical studies). Wang et al. (2003) modified the original 6-strand Tang method (Tang et al., 1994) to the 'M-Tang' method by adding a transverse component in the suture, forming an 'M' configuration in the tendon, with fewer sutures and knots on the tendon surface. This technique had a 2 mm gap formation force and ultimate strength that was similar to the original Tang method. Subsequently, Cao and Tang (2005) demonstrated a 4-strand U-shaped modification of the 6-strand Tang method, which was superior to the double Kessler repair in resistance to gap formation.

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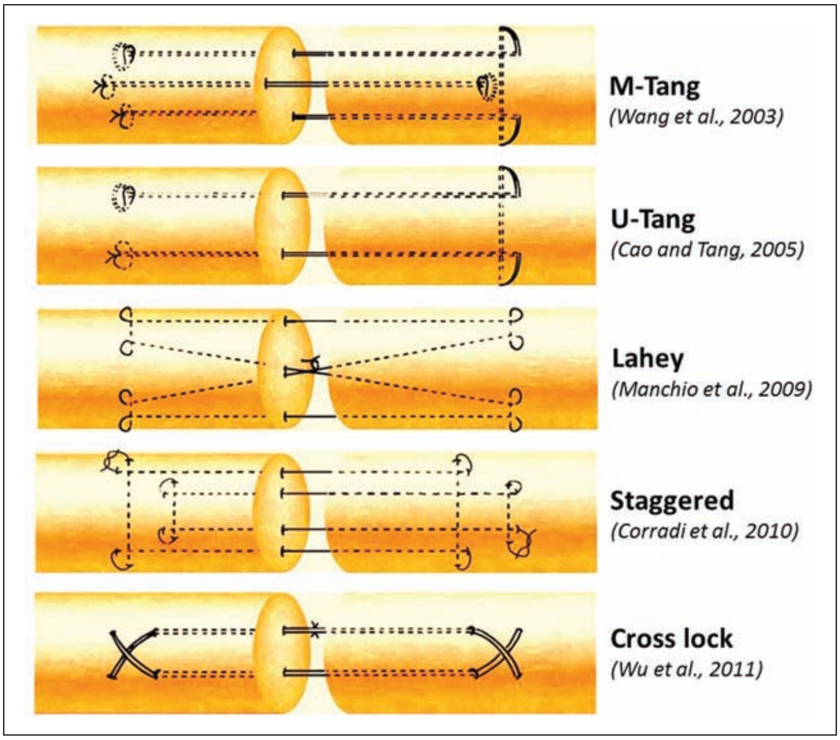

Figure 1. Newer tendon repair methods developed from biomechanical studies over the past decade.

Table 1. Some major investigations of between the novel methods in biomechanical studies.

Repair methods	Sample size	Suture	Initial gap force (SD) (N)	2 mm gap force (SD) (N)	Ultimate strength (SD) (N)
M-Tang (Wang et al., 2003)	9	4-0 Supramid	—	46.2 (5.2)	61.9 (6.0)
U-Tang (Cao and Tang., 2005)	12	4-0 Supramid	30.6 (4.0)	36.8 (4.0)	43.4 (4.3)
Lahey (Manchio et al., 2009)	10	3–0 Prolene	32.5 (—)	—	63.8 (7.5)
Staggered (Corradi et al., 2010)	10	3-0 Ethilon	—	41.3 (4.3)	88.6 (6.7)
Cross-lock (Wu et al., 2011)	12	4-0 Supramid	—	31.9 (6.1)	40.2 (3.9)

Investigators also developed new configurations in order to decrease gapping and to prevent changes in the geometry of tendon sutures. Among these configurations are the Lahey and staggered repair methods. The Lahey repair (Manchio et al., 2009) is a 4-strand cruciate repair with a Kessler-type suture at the anchor sites, which is very similar to the method described by Walbeehm et al. (2009). The difference between the two methods is that the knot is placed at the lateral longitudinal strand of the repair in the Walbeehm method. The Lahey repair method has been reported to have better ultimate strength than the 4-strand Kessler repair and the cruciate repair. Corradi et al. (2010) developed a 4-strand staggered repair technique. This method has been shown to be better than repairs such as the Strickland, Wolfe and modified Savage techniques for both 2 mm gap force or ultimate strength. Corradi et al. (2010) considered that the differences in the strength between their method and the others related to a more balanced distribution of forces across the rupture site offered by the ‘near to far, far to near’ staggering. Recently, Wu et al. (2011), Tang (2011) and Low et al. (2012) have advocated a cross-lock repair method with double-stranded suture. This method appears to be simpler to perform.

Although many techniques have been reported to have sufficient strength for early postoperative motion of the repaired tendon, some of them may be too complicated for surgical use, because of the small size of human flexor tendons. In addition, high-strength suture configurations usually result in bulky, high-friction repairs, which may hinder tendon gliding.

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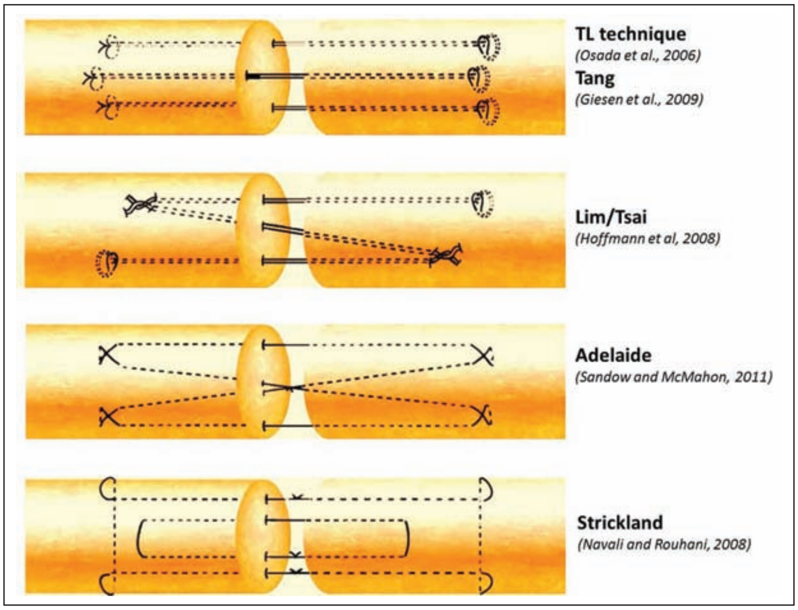

Figure 2. Newer repair methods used in clinical applications over the past decade.

Table 2. Major clinical reports and outcomes of the multi-strand tendon repair methods in the last decade.

Repair methods	Lacerations	Follow-up (months)	Functional recovery		
			Excellent/ good (%)	Fair/poor (%)	Rupture (%)
Triple-looped (Osada et al., 2006)	27 FDP	13	63/33	4/0	0
Tang (Giesen et al., 2009)	50 FPL	18	40/42*	10/8*	0
Lim/Tsai(Hoffmann et al., 2008)	50 FDP	3	42/36	22/0	2
Figure of eight (Al-Qattan, 2011)	20 FDP	22	60/20	20/0	0
Adelaide (Sandow and McMahon, 2011)	65 FDP	3	34/27	14/15	5
Strickland (Navali and Rouhani, 2008)	16 FDP	11	81/13	6/0	0

The number the functional recovery is the percentage of digits. The functional recovery was assessed according to the original criteria of Strickland and Glogovac (1980), except for those marked with *, which were assessed according to the method of Buck-Gramcko et al. (1976)
FDP: flexor digitorum profundus; FPL: flexor pollicis longus.

Clinical applications and the outcomes of newer repair methods

There have been a number of reports of excellent outcomes of zone 2 flexor tendon repairs using multi-strand techniques (see Figure 2 and Table 2 for summary). Osada et al. (2006) repaired the flexor tendons in 27 fingers with a triple-looped suture followed by controlled early active mobilization. A total of 96% of the repairs showed good or excellent results with no tendon ruptures. The triple-looped suture in this study was actually the same as the original Tang method (Tang et al., 1994). This method also showed excellent or good results in 78% (White criteria) or 82% (Buck-Gramcko criteria) of 50 flexor pollicis longus (FPL) tendon repairs reported more recently by Giesen et al. (2009). Even without circumferential sutures, no repairs ruptured in the 50 repairs reported by these authors.

The common element of the configurations in the above repairs is the Tsuge suture, which is both strong and easy to perform. The 6-strand Lim/Tsai method, which includes part of the Tsuge configuration, has been reported to lead to a better average grip strength, a significantly higher total active motion of the repaired digits, a lower complication rate and a shorter average time of treatment compared with a 2-strand modified Kessler technique (Hoffmann et al., 2008).

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The ‘three figure-of-eight’ method was introduced and clinical outcomes were reported in a series of studies (Al-Qattan, 2011; Al-Qattan and Al-Turaiki, 2009). With the same postoperative mobilization programme (a dorsal blocking splint with immediate active motion that allowed full extension at the interphalangeal joints), 98% of zone 2 flexor tendon repairs (50 fingers in 45 patients) and 80% (20 fingers in five patients) of zone 2 lacerations of both flexor tendons of all fingers in adults had excellent or good results. We note that this method only involves longitudinal sutures in its configuration without any true transverse or locking components, although the sutures grasp the full thickness substance of the tendon on each side. Further studies would be necessary to establish whether it could produce such good outcomes with clean-cut or other types of injuries.

The clinical outcomes of 4-strand core sutures have been documented in the following reports. Modified Strickland repair in flexor tendons in children had excellent or good results in 94% of 16 cases, with no rupture of the repairs after surgery (Navali and Rouhani, 2008). Sandow and McMahon (2011) used an Adelaide repair, a simplification of the Savage method, in 65 zone 1 and 2 flexor digitorum profundus (FDP) tendon lacerations and achieved a good or excellent outcome in 71% of fingers with a 4.6% rupture rate. Although the 2-strand method has been used to repair tendons for a long time, over the last decade its use has declined drastically. We believe that 4-strand or 6-strand repairs are more suitable for FDP tendon injuries in zones 1, 2 and 3. However, for the flexor digitorum superficialis (FDS) tendons in zone 2 and 3, the appropriate technique must be carefully chosen according to the size of the tendon and the location of the laceration. A 2- or 4-strand repair can be used for the FDS tendon, and a 6-strand repair is not necessary.

The Teno Fix device (Ortheon Medical, Winter Park, FL, USA) is a novel and unique attempt to strengthen tendon repairs. Although initial clinical reports have been impressive, and the design of the device is sound, this method has not been popular. The device is composed of two intratendinous stainless steel anchors (coil–core combination) that are joined by a single multifilament 2-0 stainless steel suture. In vitro and in vivo studies have shown good results of Teno Fix repairs (Su et al., 2005a; 2006; Wolfe et al., 2007). Clinically, the tendon repairs were reported to have lower rupture rates and similar functional outcomes to the 4-strand cruciate repair (Su et al., 2005b). Rocchi et al. (2008) reported 12 excellent, six good and three fair outcomes in 21 patients with Teno Fix repairs in clean-cut flexor tendon injuries in zone 2. The Teno Fix device seems to produce strong tendon repairs that effectively withstand early active finger motion and result in a quicker functional recovery. However, the device is not recommended in small tendons and if exposure is inadequate, or in the treatment of dirty, complex multiple tendon injuries and fraying tendons. A major concern in clinical use is the increase in the volume of the tendons inside the sheath–pulley area and the potential need for secondary surgery to remove the implant. These potential drawbacks have been the major hurdles in popularizing this device.

Factors influencing the outcome of flexor tendon repairs

The factors affecting the outcome of surgical repair include external and internal factors. The external factors are the treatment of the major pulleys and the FDS tendon. The internal factors are how the tendons themselves are repaired: the number of suture strands; the material properties of the sutures; the locking or grasping configuration; the surgical knots; the peripheral repairs; the purchase of the sutures; the tension of core sutures; and the direction and curvature of tendon motion. (See Figure 3 for summary and our preferred practices in dealing with these factors.)

Integrity and surgical treatment of major pulleys

How the surgical treatment of the major pulleys affects the outcome of the repaired tendon has been a major focus of investigations over recent years and accumulated knowledge in this area represents some of the major advancements in the field. In animal or cadaver studies, excision of both slips of the superficialis tendon when repairing the lacerated profundus tendon within the A2 pulley area reduces resistance to the tendon gliding or decreases adhesion formation when compared with repair of both the FDP and FDS tendons (Tang et al., 2003b; 2007; Xu and Tang, 2003). Resection of one single FDS tendon slip facilitates gliding of the repaired tendon (Tang et al., 2007; Zhao et al., 2002).

Tang (2007) has detailed how to partially vent critical pulleys at different levels of tendon lacerations. Numerous studies support the venting of a part of the A2 or A4 pulley to improve the tendon repair (Cao and Tang, 2009; Franko et al., 2011; Orkar et al., 2012; Tanaka et al., 2004a; Wu et al., 2012). The major annular pulleys (A2 and A4) and the presence of an intact

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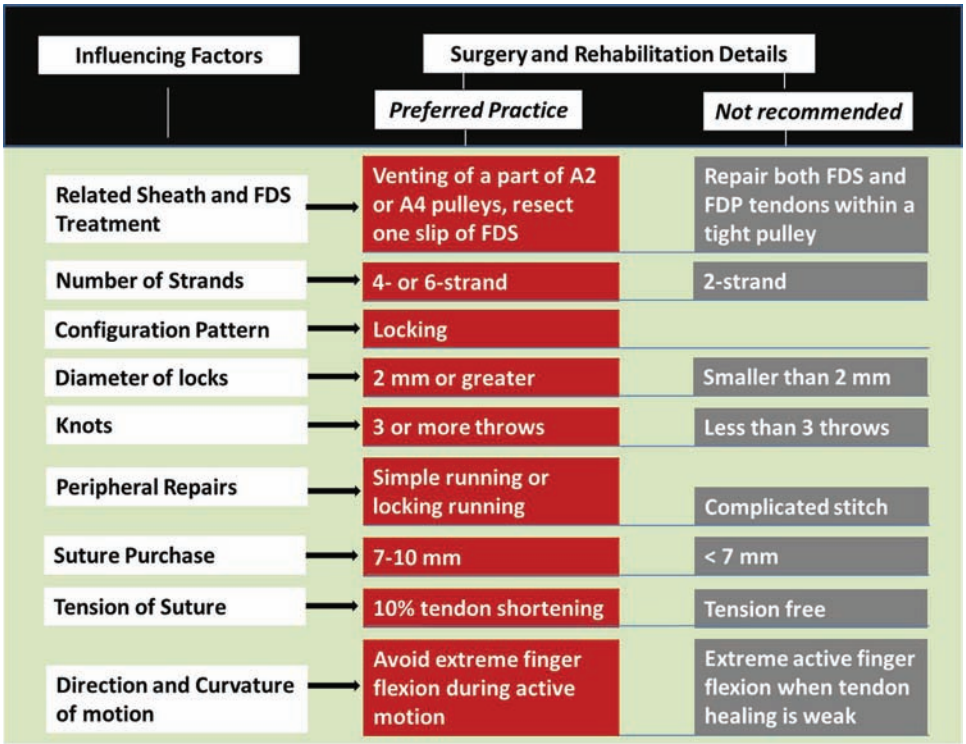

Influencing Factors	Surgery and Rehabilitation Details	
	Preferred Practice	*Not recommended*
Related Sheath and FDS Treatment	Venting of a part of A2 or A4 pulleys, resect one slip of FDS	Repair both FDS and FDP tendons within a tight pulley
Number of Strands	4- or 6-strand	2-strand
Configuration Pattern	Locking	
Diameter of locks	2 mm or greater	Smaller than 2 mm
Knots	3 or more throws	Less than 3 throws
Peripheral Repairs	Simple running or locking running	Complicated stitch
Suture Purchase	7-10 mm	< 7 mm
Tension of Suture	10% tendon shortening	Tension free
Direction and Curvature of motion	Avoid extreme finger flexion during active motion	Extreme active finger flexion when tendon healing is weak

Figure 3. Major factors affecting the strength of surgical repair. The preferred practices and those not recommended in surgery and rehabilitation are demonstrated.
FDS: flexor digitorum superficialis.

FDS tendon are two major factors that affect gliding of the profundus tendon. The treatment of these structures should be selected according to the site of tendon injury. If the repair lies in the region of the A2 pulley, it is recommended to release a part of the A2 pulley and/or resect at least one slip of the FDS tendon to avoid crowding of the narrow space within the A2 pulley, which would be additionally aggravated by the postoperative oedema of the tendon (Figure 3). Partial release of the A2 pulley may also be done if a repair site, although not within the A2 pulley, will encroach on the rim of A2 pulley during the full passive range of finger flexion. These important points have been emphasized recently for achieving better clinical outcomes in both primary and secondary tendon surgery (Elliot and Giesen, 2013; Tang, 2013).

Number of strands of the core suture

It has been proven in many in vitro studies and is now widely accepted, that increasing the suture number across the repair site proportionally increases the resistance to gap formation, failure strength or fatigue strength during cyclic loading (Barrie et al., 2000; Sanders et al., 2001).

Currently, a 2-strand suture is considered to have insufficient mechanical strength and does not safely tolerate active tendon motion during postoperative exercise. Four-strand repairs have been the most investigated techniques in biomechanical studies in the last decades because these kinds of repairs provide sufficient strength and are, in most cases, easy to perform (Figure 3) (Cao and Tang, 2005; Lawrence et al., 2005; Smith and Evans, 2001; Tan et al., 2003; Vigler et al., 2008; Wu et al., 2011; Xie et al., 2005). Four-strand core repairs are now the main techniques used clinically in digital flexor tendons (Tang et al., 2013a). In vivo studies in chickens have demonstrated that a 4-strand repair does not increase adhesion or resistance compared with a 2-strand repair (Strick et al., 2004). According to these findings, 4-strand repairs seem to represent the proper combination of improved tensile strength and gliding characteristics, as well as being technically easy to perform. Six- or 8-strand repairs have been developed and are in use in a number of units. There have been no studies to compare the outcomes of 4-strand or 6-strand repairs. However, 6- or 8-strand repairs would presumably provide a greater safety margin during postoperative active finger motion.

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Table 3. Commonly investigated and clinically used suture materials for tendon repairs.

Materials	Description	Main manufacturers	Usage	Advantages	Disadvantages
Stainless steel	Stainless steel	Ethicon, Somerville, NJ, USA	Used 30–40 years ago	Highest stiffness and tensile strength	Kinking and difficult handling
Ethibond	Coated braided polyester suture	Ethicon, Somerville, NJ, USA	Currently used	High tensile strength and easy handling	Poor knot-holding
Ethilon	Monofilament nylon suture	Ethicon, Somerville, NJ, USA	Currently used	Easy handling	Comparatively inferior strength
Supramid	Braided nylon encased in smooth shell	S. Jackson, Alexandria, VA, USA	Currently used	Looped suture and easy handling	Comparatively inferior strength
Prolene	Monofilament polypropylene suture	Ethicon, Somerville, NJ, USA	Currently used, mostly in peripheral suture	Good knot-holding and less bulk to knot	Comparatively inferior strength
FiberWire	Braided polyblend polyethylene suture	Arthrex, Naples, FL, USA	Increasingly used	Higher stiffness and tensile strength	Poor knot-holding
NiTi	Nickel–titanium shape-memory alloy	Orfix, Raahe, Finland	New metal material	Superior biocompatibility, tensile strength and stiffness	
Barbed suture	Glycolic-carbonate	Covidien Deutschland GmbH, Neustadt, Germany	Rarely used	Increased suture–tendon interaction, knotless,	Suture burden, tissue handling
PDS	Polyglycolide-trimethylene carbonate	Johnson & Johnson, New Brunswick, NJ, USA	Less used	Absorbable	Loss in tensile strength of suture over time
Maxon	Bioabsorbable, polyglyconate suture	Davis & Geck, Danbury, CT, USA	Less used	Absorbable	Loss in tensile strength of suture over time

Suture materials

The ideal suture material should have high tensile strength, be easy to handle and induce as little tissue reaction as possible. Currently, there is no consensus on the best choice of suture material for tendon repairs, and a surgeon's preference is mostly based on individual experience rather than scientific evidence. The commonly investigated and used suture materials in tendon repair are listed in Table 3, together with the details of their manufacturers. To date, Ethibond has been reported to have higher tensile strength and stiffness (Lawrence and Davis, 2005; Silva et al., 2009). Ethilon, Prolene, and Supramid have been reported to have slightly lower strengths than Ethibond (Brockardt et al., 2009; Mishra et al., 2003).

FiberWire, a braided polyblend polyethylene suture, has been increasingly used for tendon repair over the past 10 years. In vitro studies suggest that this material is significantly stronger than Ethibond, Prolene and nylon. FiberWire had a similar ultimate force and even higher stiffness when compared with stainless steel in the 4-strand cross-lock cruciate repair (Lawrence and Davis, 2005; McDonald et al., 2013) and outperformed both Ethibond and nylon sutures in a locked MGH (*Massachusetts* General Hospital) repair (Miller et al., 2007). A two-strand Kessler repair with FiberWire was equivalent to a 4-stranded cruciate repair with Supramid (Brockardt et al., 2009). Gan et al. (2012) were able to achieve up to 124 N in ultimate tensile strength and 48 N of gap force with loop-suture of FiberWire when repairing porcine tendons using a modified Lim-Tsai 6-strand suture technique. FiberWire is also a low-friction suture material (Silva et al., 2009). However, a FiberWire suture is actually greater in diameter than many other sutures in the same size category. If strength is considered relative to cross-sectional area, FiberWire is only 10% stronger than Prolene and 25% stronger than Ticron (Syneture, Norwalk, CT, USA) (Scherman et al., 2010). In addition, its poor knot-holding characteristics caused by knot unravelling may be a concern and a minimum of six-knot throws was recommended to prevent suture unravelling (Le et al., 2012; Moriya et al., 2012; Waitayawinyu et al., 2008).

Nickel–titanium (NiTi) wire, with its excellent strength and stiffness, good super-elastic properties and easy handling, has been reported to be a

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promising new metal suture for tendon repair (Karjalainen et al., 2010a, 2010b; Kujala et al., 2004). Core and circumferential repairs have been recommended with 200 μm and 100 μm NiTi wires, respectively. Karjalainen et al. (2012) further demonstrated that the multifilament nitinol sutures had a better suture grip than the monofilament one. However, in vivo studies are needed before clinical use.

A barbed suture has been suggested for its characteristics of improved tendon–suture interaction and the lack of knots in the tendon repair. However, significant advantages in repair strength over the traditional knotted repairs remain to be demonstrated; published data show that the strength of 4-strand knotless technique with barbed suture repair is similar to a 4-strand core suture repair using 3-0 or 4-0 sutures (Marrero-Amadeo et al., 2011; McClellan et al., 2011; Zeplin et al., 2011).

Absorbable sutures (e.g. Maxon, polydioxanone (PDS)) have been shown to have sufficient tensile strength to withstand active tendon mobilization (Wada et al., 2001, 2002). Caulfield et al. (2008) confirmed that absorbable sutures (PDS or Maxon) achieved excellent and good results, comparable with those of non-absorbable sutures. However, their reduction of tensile strength over time and high elasticity may prevent their wide clinical use in tendon repair.

Core suture diameters

Until now, 2-0, 3-0, 4-0 and 5-0 sutures have all been used in tendon repairs with 3-0 and 4-0 sutures being the most commonly used (Brockardt et al., 2009; Hwang et al., 2009; Tang et al., 2013a; Vizesi et al., 2008). A 3-0 suture has been recommended for its greater strength in both cyclic loading and linear tests (Barrie et al., 2001; Taras et al., 2001). A 4-0 suture was as strong as a 3-0 suture when used in a 4-strand locked cruciate core stitch (Alavanja et al., 2005). A 2-0 suture has been less used because of the increased bulk at the repair site, and a 5-0 suture has insufficient strength when used as a core suture.

Configurations of locking or grasping loops in the repairs

The concepts of 'grasping' and 'locking' existed long before their popular use as a description of configurations in tendon repair methods (Pennington, 1979). A heated debate about the superiority of grasping or locking in tendon repairs has lasted for decades. Supporters of locking tendon–suture configurations advocate using Pennington locks in their repairs to reduce tendon gapping and increase the repair strength (Hatanaka et al., 2000; Hotokezaka and Manske, 1997; Wada et al., 2000). Other investigations have stated different opinions – locking patterns do not seem to add much advantage to a repair when compared with grasping patterns (Barrie et al., 2001; Tanaka et al., 2004b; Wu and Tang, 2011). In practice it is sometimes difficult to ascertain the relative location of the transverse and longitudinal sutures, thus it can be hard to know whether a Pennington locking is truly incorporated. Although we acknowledge a certain degree of superiority in locking repair methods, such as the cross- and circle-locks, these should not be overvalued and surgeons should not rely too much on them to achieve a good tendon repair. Other factors, such as the number of strands, the suture purchase and the diameter of the sutures are just as important as adding locks to the repair. In addition, Pennington locking does not have a typical locking configuration, as a cross-lock or a circle-lock does. The Pennington locks add only very small resistance to gapping to a 2-strand repair and add no strength to a 4-strand repair (Wu and Tang, 2011).

Some investigators have incorporated cross- or circle-locks in their core sutures (Barrie et al., 2001; Croog et al., 2007; Tan and Tang, 2004; Wu et al., 2011; Xie and Tang, 2005; Xie et al., 2005). The diameter of the lock is more important than which locks are incorporated. Locks of 2 mm diameter and locking circles perpendicular to the long axis of the tendon have been proven to be important to the holding capacity of the locks. A smaller lock is very easy to tear from the tendon and thus should be avoided (Xie and Tang, 2005; Xie et al., 2005). It is important to find a balance between the strength of the suture material and the gripping capacity of different suture configurations. If the strength of the material is less than the grip capacity of a loop, the suture would rupture rather than pull out and the potential benefits of such locking loops would be lost.

The cruciate repair has become a popular method. Mechanically, modifying the grasping cruciate repair to a cruciate repair with cross-locks was found to be better than several other methods that incorporated Kessler-type repairs (Croog et al., 2007, Waitayawinyu et al., 2008). The superiority of these cruciate-type methods over Kessler-type methods may be explained by the findings of two reports about the relationship between the core suture geometry and tendon deformation (Peltz et al., 2010; Walbeehm et al., 2009). With Kessler-type repairs, shortening of the transverse components, transformation of the Kessler loop to form a U-shaped configuration, tendon buckling and change in the angle of the Kessler loop relative to the longitudinal axis of the tendon elongate the tendon repair and a gap develops more easily during

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tendon loading. The cruciate-type repair does not have transverse suture components, and withstands the longitudinal axial forces more efficiently and is less likely to elongate. The ideal loop size in cruciate-type repairs has also been investigated, with a cruciate loop that is 25% of the tendon width being recommended (Dona et al., 2004; Peltz et al., 2011).

Knots

Knot tying has been reported to markedly influence the strength of the repair. Flexor tendon repairs usually rupture at the knots, which are the weakest point in a suture construction. The effect of the location of suture knots on tendon repair strength has been studied. In an in vitro study, Aoki et al. (1995) indicated that the knots should be located outside the repair on the tendon surface and there should be as few as possible. However, in vivo, suture material within the repair site was shown to have no deleterious effects on tensile strength and may even stimulate tendon healing (Pruitt et al., 1996). The number of knots has been proven to alter the repair strength in vitro. A 1-knot 4-strand double-modified Kessler technique was significantly stronger than a 2-knot technique (Rees et al., 2009). It is thought that all strands in the repair with one knot are carrying equal load, while with two knots the unequal loading of the strands lead to a high risk of early failure. In addition, the number of knot throws is worth noting: at least three throws are needed to tie a knot firmly (Figure 3) and more with FiberWire (Le et al., 2012; Waitayawinyu et al., 2008).

Peripheral repairs

Inserting peripheral epitendinous sutures has been shown to increase repair strength and reduce the gapping between tendon ends, as well as to improve the gliding function of the tendon within the sheath. Peripheral suture techniques developed in 1980s and 1990s include the Lin-locking, Halsted mattress and cross-stitch.

In the last decade, more complex peripheral repairs – the interlocking cross-stitch (IXS), interlocking horizontal mattress (IHM), cross-linked Silfverskiöld and Lembert – have been shown to be superior to simple running or simple cross-stitch patterns (Dona et al., 2003; Mishra et al., 2003; Moriya et al., 2010; Takeuchi et al., 2010). However, most of these studies have not looked at the gliding properties of repaired tendons with different peripheral sutures. An ideal peripheral repair should minimize gliding friction between the repaired tendon and the surrounding tissues. To date, the simple running peripheral suture remains widely used, probably because the complexity of many other techniques limits their clinical application (Tang et al., 2013a). We do not recommend complex peripheral sutures, because they are difficult to insert and result in a large exposure of the suture over the tendon surface.

The depth and purchase of peripheral sutures significantly affect the tensile strength of repaired tendons. With deep peripheral sutures and an increased distance of the peripheral sutures from the repair site, the tendons have been found to have significantly greater mean loads to failure (Diao et al., 1996; Merrell et al., 2003). We observed that a peripheral suture with an identical purchase of 1.5 mm and a depth of 1 mm would effectively add strength to the core suture without adding too much bulk to the lacerated edges of tendon ends (Cao et al., 2006; Wu and Tang, 2011).

Recent studies about the effect of partial versus complete peripheral repair on gap formation and tendon strength have shown some differences. Ansari et al. (2009) showed that the use of circumferential repairs covering only the palmar half of the tendon surface could significantly increase the gap resistance and thus can be used together with a complex core suture, though a complete peripheral repair was even more effective in resisting gap formation at the repair site. Takeuchi et al. (2011) found that a complete circumferential repair with interlocking cross-stitches was better than a peripheral suture covering only one-half or two-thirds of the tendon circumference. Wit et al. (2013) found that the geometry of core sutures has a great influence on the strength, but peripheral sutures did not have a significant mechanical effect on the tested core sutures. Nevertheless, the most interesting recent clinical finding is that a strong core suture without peripheral sutures produced no postsurgical rupture of the repair, indicating a new concept of flexor tendon repair that does not incorporate any peripheral sutures in the presence of a strong core suture (Giesen et al., 2009).

Purchase of the core suture

The influence of core suture purchase, described as the distance between core suture placement and the cut end of the tendon, was first investigated in in vitro studies of obliquely cut tendon repair (Tan and Tang, 2004; Tang et al., 2003a), followed by studies of transversely lacerated tendon repairs in the same group (Cao et al., 2006; Tang et al., 2005). Lengthening the suture purchase was found to effectively improve the repair strength and an optimal length between 0.7

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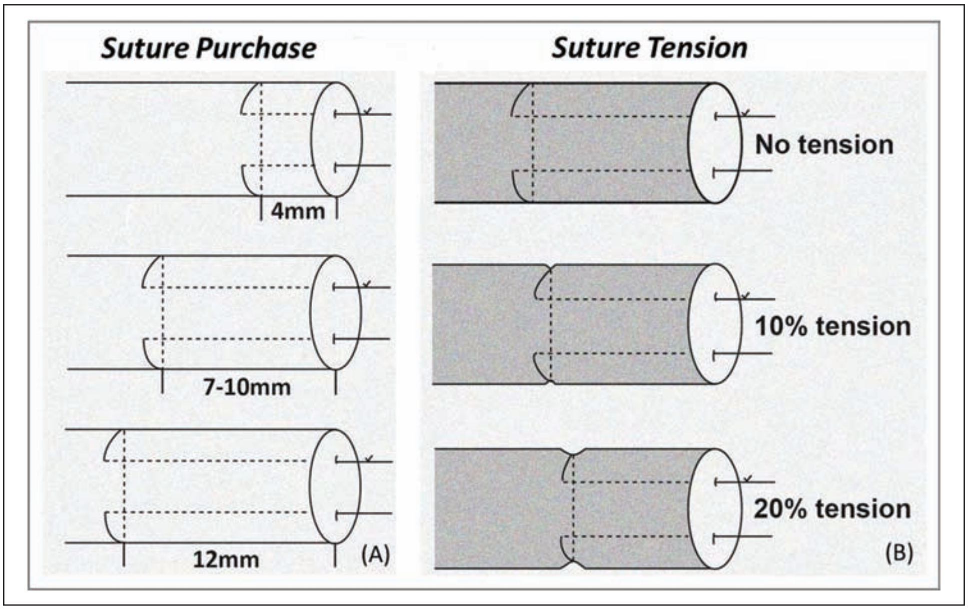

Figure 4. Different lengths of purchase and tensions of core suture. The optimal length of purchase is 7–10 mm. Increasing the length to 12 mm does not increase the strength of the repair, whereas a length of 4 mm or less results in significantly weaker repairs. Adding slight tension to core suture by a 10% tendon–segment shortening substantially increases the gap resistance in the surgical repair.

and 1.0 cm was recommended (Figures 3 and 4). Possible mechanisms that account for this increase in strength are that increasing the length of suture purchase provides the tendon with a greater suture–tendon interaction, a more secure grip power of the sutures on the tendon surface and an increased stiffness to counteract tensile forces. The work of Tang and his colleagues was supported by two recent studies by Kim et al. (2009) and Lee et al. (2010), which have also shown that tendons repaired with the cross-locked cruciate – interlocking horizontal mattress method with a 10 mm suture purchase have a low increase in work of flexion, high failure strength and high resistance to gapping.

Tension across the core suture

This issue is rarely discussed though inevitably faced when tightening sutures and tying knots. Tang (2007) highlighted that the addition of slight tension to the core suture would be beneficial in withstanding the pull of muscles after surgery and reduced the risk of gapping during early tendon motion. This was confirmed in a recent report (Wu and Tang, 2012), which showed that 10% of tendon shortening markedly increased the gap formation forces without any obvious increase in tendon bulkiness. The ultimate strength was not affected by the different tensions in 2-strand or 4-strand repairs. Quite similarly, Vanhees et al. (2013) have reported that pretensioning with 10 to 15 N at the suture–tendon interface before tying the knot has a beneficial effect on both the tendon gap formation and the peak force to failure. Although it is now not possible to match the ‘degree of tendon shortening’ with ‘the pretension load’, we truly believe that preloading helps to even out the load on the suture strands.

Gapping between tendon stumps will lead to poor tendon healing, adhesions and catching of the tendon over the pulley. Adding a certain baseline tension to the suture equalizes the tension on the strands of the repair, which prevents gapping during early active motion of the tendon. The need to avoid a loose repair of the tendon is also emphasized by Lalonde and Kozin (2011) and Lalonde and Martin (2013). A loose repair has been found to gap very easily during intra-operative testing of active motion of the repaired tendon. Using a cyclical loading programme to simulate the early rehabilitation regime, Smith et al., (2012) have proven that pre-tensioning of Prolene sutures results in significantly less creep (and thereby the formation of a ‘gap’ in tendon repairs) with no effect on the ultimate tensile strength, but this was not so for Ethibond. We have developed a method to quantify three-dimensional gap areas of tendon under load in mechanical testing (Tang et al., 2013b). We also

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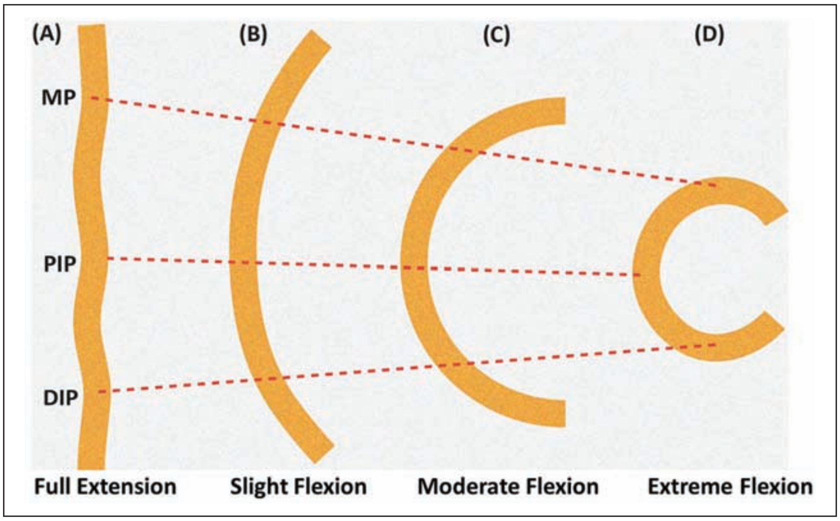

Figure 5. The gliding angle and curvature of tendon motion arcs change with the increasing flexion of finger. (A) At the full extension of the finger, the tendon shows physiological curves within the digital flexor tendon sheath. (B) When the finger is slightly flexed, the curvature of the tendon is small and the tendon sustains a very small amount of bending force. (C) When the tendon is increasingly flexed, the tendon curvature increases and the bending force increases accordingly. (D) When the finger is at the extreme of flexion, the curvature of the tendon gliding arc becomes nearly circular and the radius of the arc is very small. During the course of digital flexion, the flexor tendon sustains an increasingly greater bending force and the surgical repair becomes progressively weakened as the finger flexes.
MP: metacarpophalangeal joint; PIP: proximal interphalangeal joint; DIP: distal interphalangeal joint.

propose to do a three-step test of the repair site before closure of the surgical incision, to make sure that the repair does not gap or impinge on the rigid pulley edge during simulated active finger flexion (Tang, 2013).

Direction and curvature of tendon motion

Tension direction and curvature of tendon motion arcs have been shown to alter tendon repair strength (Tang et al., 2001; Tang et al., 2003c). The gap formation force and ultimate strength decreased as angles of tension increased from 0° to 90° and reached the lowest point at 90° (Tang et al., 2001). With a decreased radius of curvature, the tendon repair strength decreased considerably (Tang et al., 2003c). These two findings are particularly important in clinical situations in which the repaired tendon must glide along curvatures over the sheaths, pulleys or joints, which is quite different from the experimental situations where tendons undergo linear loading. During progressive flexion of the finger when the angle and the curvature of the arcs of tendon motion increase, the tendon sustains an increasingly greater bending force along the arc and thus the repair becomes weakened (Figure 5). The decrease in repair strength during angular pulling should be considered while planning active finger flexion. These findings imply that the tendon is particularly weak at the position of extreme flexion, and active motion of the repaired finger to this position should be avoided when tendon healing is still weak. We suggest that early active finger flexion should not exceed two-thirds of the total digital flexor arc in the first 3 weeks after surgery; in the initial 1 or 2 weeks after surgery, it may be wise to keep the active finger flexion within only one-third to half of the total range of finger motion. We believe that 'partial active digital motion' is important in ensure safe active finger motion.

Havulinna et al. (2013) reported that the strength of a Kessler core suture in zones 1 and 2 (26.7 N, SD 5.6) was significantly higher than the mean strength in zone 3 (17.7 N, SD 5.4) in cadaveric hands. They suggest that the difference is owing to variations of the structure of the tendon in different areas, and repair in zone 3 could be weaker than zone 1 and 2 flexor tendon repair. However, because zone 3 flexor tendons are less bent and glide in a fairly straight path during hand motion, and as they are not restricted by the sheath, we believe zone 3 flexor tendons are less vulnerable to disruption. The Pulvertaft weave suture is used as a standard way to make the proximal tendon junction during secondary tendon reconstruction, which is different from the end-to-end repair discussed above. The Pulvertaft weave usually has adequate strength and it rarely fails clinically. However,

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some investigators have improved on its strength by the use of a loop weave (Crook et al., 2013).

Conclusions

Progress in tendon repair has been achieved steadily over the past decade. The most important clinical change seen in this period has been the adoption of multi-strand core suture techniques, typically the 4-strand repairs, in repairing digital tendons. Based on the information available, we recommend that at least a 4-strand core repair (made with a 4-0 or 3-0 suture) should be used for a cut flexor digitorum profundus tendon in the digits. We believe that six or more core sutures add safety to active digital motion after surgery. A 'core suture-only' tendon repair represents a new approach during this period. If a peripheral suture is not added after core suturing, a 6-strand repair is recommended, and ensuring slight tension of the core suture is advised to prevent gapping after surgery.

The major advancement in the basic science of flexor tendon repair is the understanding of the multiple factors that may affect the strength of surgical repair. The tension of the core suture, the core suture purchase, the suture anchor sizes, the curvature of tendon gliding and the presence of intact major pulleys affect the repair strength, as well as those factors – such as incorporation of locking repair components, the number of suture strands and the type of postoperative motion – that are already known. These recent findings indicate that a slight tension within the core suture, adequate core suture purchase (greater than 7–10 mm) and suture anchor sizes of 2 mm or more are important, or even critical, for the baseline strength of surgical repair. Postoperatively, a limited active range of flexion over one- or two-thirds of the flexion arc would prevent the repaired tendon bending too much, thus reducing the chances of rupture of the repair. However, most studies have been on cadaver or animal tendons in vitro. Such studies should be followed with in vivo investigations and clinical application in patients to obtain a more complete assessment of tendon repairs.

Conflict of interests

None declared.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

Alavanja G, Dailey E, Mass DP. Repair of zone II flexor digitorum profundus lacerations using varying suture sizes: a comparative biomechanical study. J Hand Surg Am. 2005, 30: 448–54.

Al-Qattan MM. Zone 2 lacerations of both flexor tendons of all fingers in the same patient. J Hand Surg Eur. 2011, 36: 205–9.

Al-Qattan MM, Al-Turaiki TM. Flexor tendon repair in zone 2 using a six-strand 'figure of eight' suture. J Hand Surg Eur. 2009, 34: 322–8.

Ansari U, Lawson RD, Peterson JL, Appleyard RC, Tonkin MA. Effect of partial versus complete circumferential repair on flexor tendon strength in cadavers. J Hand Surg Am. 2009, 34: 1771–6.

Aoki M, Pruitt DL, Kubota H, Manske PR. Effect of suture knots on tensile strength of repaired canine flexor tendons. J Hand Surg Br. 1995, 20: 72–5.

Barrie KA, Tomak SL, Cholewicki J, Wolfe SW. The role of multiple strands and locking sutures on gap formation of flexor tendon repairs during cyclical loading. J Hand Surg Am. 2000, 25: 714–20.

Barrie KA, Tomak SL, Cholewicki J, Merrell GA, Wolfe SW. Effect of suture locking and suture caliber on fatigue strength of flexor tendon repairs. J Hand Surg Am. 2001, 26: 340–6.

Brockardt CJ, Sullivan LG, Watkins BE, Wongworawat MD. Evaluation of simple and looped suture and new material for flexor tendon repair. J Hand Surg Eur. 2009, 34: 329–32.

Buck-Gramcko D, Dietrich FE, Gogge S. Evaluation criteria in follow-up studies of flexor tendon therapy [in German]. Handchirurgie 1976, 8: 65–9.

Cao Y, Tang JB. Biomechanical evaluation of a four-strand modification of the Tang method of tendon repair. J Hand Surg Br. 2005, 30: 374–8.

Cao Y, Tang JB. Strength of tendon repair decreases in the presence of an intact A2 pulley: biomechanical study in a chicken model. J Hand Surg Am. 2009, 34: 1763–70.

Cao Y, Zhu B, Xie RG, Tang JB. Influence of core suture purchase length on strength of four-strand tendon repairs. J Hand Surg Am. 2006, 31: 107–12.

Caulfield RH, Maleki-Tabrizi A, Patel H, Coldham F, Mee S, Nanchahal J. Comparison of zones 1 to 4 flexor tendon repairs using absorbable and unabsorbable four-strand core sutures. J Hand Surg Eur. 2008, 33: 412–7.

Corradi M, Bellan M, Frattini M, Concari G, Tocco S, Pogliacomi F. The four-strand staggered suture for flexor tendon repair: *in vitro* biomechanical study. J Hand Surg Am. 2010, 35: 948–55.

Croog A, Goldstein R, Nasser P, Lee SK. Comparative biomechanic performances of locked cruciate four-strand flexor tendon repairs in an ex vivo porcine model. J Hand Surg Am. 2007, 32: 225–32.

Crook T, Tawfik J, Bertollo N, Wheen DJ, Scougall PJ, Walsh WR. Biomechanical assessment of a novel tendon junction. J Hand Surg Eur. 2013, 38: 795–800.

Elliot D, Giesen T. Primary flexor tendon surgery: The search for a perfect result. Hand Clin. 2013, 29: 191–206.

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Diao E, Hariharan JS, Soejima O, Lotz JC. Effect of peripheral suture depth on strength of tendon repairs. J Hand Surg Am. 1996, 21: 234–9.

Dona E, Gianoutsos MP, Walsh WR. Optimizing biomechanical performance of the 4-strand cruciate flexor tendon repair. Hand Surg Am. 2004, 29: 571–80.

Dona E, Turner AW, Gianoutsos MP, Walsh WR. Biomechanical properties of four circumferential flexor tendon suture techniques. J Hand Surg Am. 2003, 28: 824–31.

Franko OI, Lee NM, Finneran JJ et al. Quantification of partial or complete A4 pulley release with FDP repair in cadaveric tendons. J Hand Surg Am. 2011, 36: 439–45.

Gan AW, Neo PY, He M, Yam AK, Chong AK, Tay SC. A biomechanical comparison of 3 loop suture materials in a 6-strand flexor tendon repair technique. J Hand Surg Am. 2012, 37: 1830–4.

Giesen T, Sirotakova M, Copsey AJ, Elliot D. Flexor pollicis longus primary repair: further experience with the tang technique and controlled active mobilization. J Hand Surg Eur. 2009, 34: 758–61.

Hatanaka H, Zhang J, Manske PR. An in vivo study of locking and grasping techniques using a passive mobilization protocol in experimental animals. J Hand Surg Am. 2000, 25: 260–9.

Hoffmann GL, Büchler U, Vögelin E. Clinical results of flexor tendon repair in zone II using a six-strand double-loop technique compared with a two-strand technique. J Hand Surg Eur. 2008, 33: 418–23.

Hotokezaka S, Manske PR. Differences between locking loops and grasping loops: effects on 2-strand core suture. J Hand Surg Am. 1997, 22: 995–1003.

Havulinna J, Leppänen OV, Göransson H. The suture loop holding capacity of flexor digitorum profundus tendon within and outside the digital tendon sheath. J Hand Surg Eur. 2013, 38: 801–4.

Hwang MD, Pettrone S, Trumble TE. Work of flexion related to different suture materials after flexor digitorum profundus and flexor digitorum superficialis tendon repair in zone II: a biomechanical study. J Hand Surg Am. 2009, 34: 700–4.

Karjalainen T, Göransson H, Viinikainen A, Jämsä T, Ryhänen J. Nickel-titanium wire as a flexor tendon suture material: an ex vivo study. J Hand Surg Eur. 2010a, 35: 469–74.

Karjalainen T, He M, Chong AK, Lim AY, Ryhänen J. Nickel-titanium wire in circumferential suture of a flexor tendon repair: a comparison to polypropylene. J Hand Surg Am. 2010b, 35: 1160–4.

Karjalainen T, He M, Chong AK, Lim AY, Göransson H, Ryhänen J. Comparison of the holding capacity of round monofilament, round multifilament, and flat multifilament nitinol suture loops in human cadaveric flexor tendon. J Hand Surg Eur. 2012, 37: 459–63.

Kim JB, de Wit T, Hovius SE, McGrouther DA, Walbeehm ET. What is the significance of tendon suture purchase? J Hand Surg Eur. 2009, 34: 497–502.

Kujala S, Pajala A, Kallioinen M, Pramila A, Tuukkanen J, Ryhänen J. Biocompatibility and strength properties of nitinol shape memory alloy suture in rabbit tendon. Biomaterials. 2004, 25: 353–8.

Lalonde DH, Kozin S. Tendon disorders of the hand. Plast Reconstr Surg. 2011, 128: 1e–14e.

Lalonde DH, Martin AL. Wide-awake flexor tendon repair and early tendon mobilization in zones 1 and 2. Hand Clin. 2013, 29: 207–13.

Lawrence TM, Davis TR. A biomechanical analysis of suture materials and their influence on a four-strand flexor tendon repair. J Hand Surg Am. 2005, 30: 836–41.

Lawrence TM, Woodruff MJ, Aladin A, Davis TR. An assessment of the tensile properties and technical difficulties of two- and four-strand flexor tendon repairs. J Hand Surg Br. 2005, 30: 294–7.

Le SV, Chiu S, Meineke RC, Williams P, Wongworawat MD. Number of suture throws and its impact on the biomechanical properties of the four-strand cruciate locked flexor tendon repair with FiberWire. J Hand Surg Eur. 2012, 37: 826–31.

Lee SK, Goldstein RY, Zingman A, Terranova C, Nasser P, Hausman MR. The effects of core suture purchase on the biomechanical characteristics of a multistrand locking flexor tendon repair: a cadaveric study. J Hand Surg Am. 2010, 35: 1165–71.

Low TH, Ahmad TS, Ng ES. Simplifying four-strand flexor tendon repair using double-stranded suture: a comparative ex vivo study on tensile strength and bulking. J Hand Surg Eur. 2012, 37: 101–8.

Manchio JV, Shashikant MP, Shrivastava A, Weinzweig J, Vernadakis AJ. Evaluation of a new 4-strand flexor tendon repair in a cadaveric porcine model. J Hand Surg Am. 2009, 34: 102–7.

Marrero-Amadeo IC, Chauhan A, Warden SJ, Merrell GA. Flexor tendon repair with a knotless barbed suture: a comparative biomechanical study. J Hand Surg Am. 2011, 36: 1204–8.

McClellan WT, Schessler MJ, Ruch DS, Levin LS, Goldner RD. A knotless flexor tendon repair technique using a bidirectional barbed suture: an ex vivo comparison of three methods. Plast Reconstr Surg. 2011, 128: 322e–27e.

McDonald E, Gordon JA, Buckley JM, Gordon L. Comparison of a multifilament stainless steel suture with FiberWire for flexor tendon repairs – an in vitro biomechanical study. J Hand Surg Eur. 2013, 38: 418–23.

Merrell GA, Wolfe SW, Kacena WJ, Gao Y, Cholewicki J, Kacena MA. The effect of increased peripheral suture purchase on the strength of flexor tendon repairs. J Hand Surg Am. 2003, 28: 464–8.

Miller B, Dodds SD, deMars A, Zagoreas N, Waitayawinyu T, Trumble TE. Flexor tendon repairs: the impact of FiberWire on grasping and locking core sutures. J Hand Surg Am. 2007, 32: 591–6.

Mishra V, Kuiper JH, Kelly CP. Influence of core suture material and peripheral repair technique on the strength of Kessler flexor tendon repair. J Hand Surg Br. 2003, 28: 357–62.

Moriya T, Larson MC, Zhao C, An KN, Amadio PC. The effect of core suture flexor tendon repair techniques on gliding

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resistance during static cycle motion and load to failure: a human cadaver study. J Hand Surg Eur. 2012, 37: 316–22.

Moriya T, Zhao C, An KN, Amadio PC. The effect of epitendinous suture technique on gliding resistance during cyclic motion after flexor tendon repair: a cadaveric study. J Hand Surg Am. 2010, 35: 552–8.

Navali AM, Rouhani A. Zone 2 flexor tendon repair in young children: a comparative study of four-strand versus two-strand repair. J Hand Surg Eur. 2008, 33: 424–9.

Orkar KS, Watts C, Iwuagwu FC. A comparative analysis of the outcome of flexor tendon repair in the index and little fingers: does the little finger fare worse? J Hand Surg Eur. 2012, 37: 20–6.

Osada D, Fujita S, Tamai K, Yamaguchi T, Iwamoto A, Saotome K. Flexor tendon repair in zone II with 6-strand techniques and early active mobilization. J Hand Surg Am. 2006, 31: 987–92.

Peltz TS, Haddad R, Walsh WR. The change in three-dimensional geometry of the Kessler flexor tendon repair under tension: a qualitative assessment using radiographs. J Hand Surg Eur. 2010, 35: 676–7.

Peltz TS, Haddad R, Scougall PJ, Nicklin S, Gianoutsos MP, Walsh WR. Influence of locking stitch size in a four-strand cross-locked cruciate flexor tendon repair. J Hand Surg Am. 2011, 36: 450–5.

Pennington DG. The locking loop tendon suture. Plast Reconstr Surg. 1979, 63: 648–52.

Pruitt DL, Aoki M, Manske PR. Effect of suture knot location on tensile strength after flexor tendon repair. J Hand Surg Am. 1996, 21: 969–73.

Rees L, Matthews A, Masouros SD, Bull AM, Haywood R. Comparison of 1- and 2-knot, 4-strand, double-modified Kessler tendon repairs in a porcine model. J Hand Surg Am. 2009, 34: 705–9.

Rocchi L, Merolli A, Genzini A, Merendi G, Catalano F. Flexor tendon injuries of the hand treated with TenoFix: mid-term results. J Orthop Traumatol. 2008, 9: 201–8.

Sanders DW, Milne AD, Johnson JA, Dunning CE, Richards RS, King GJ. The effect of flexor tendon repair bulk on tendon gliding during simulated active motion: an *in vitro* comparison of two-strand and six-strand techniques. J Hand Surg Am. 2001, 26: 833–40.

Sandow MJ, McMahon M. Active mobilisation following single cross grasp four-strand flexor tenorrhaphy (Adelaide repair). J Hand Surg Eur. 2011, 36: 467–75.

Scherman P, Haddad R, Scougall P, Walsh WR. Cross-sectional area and strength differences of FiberWire, Prolene, and Ticron sutures. J Hand Surg Am. 2010, 35: 780–4.

Silva JM, Zhao C, An KN, Zobitz ME, Amadio PC. Gliding resistance and strength of composite sutures in human flexor digitorum profundus tendon repair: an *in vitro* biomechanical study. J Hand Surg Am. 2009, 34: 87–92.

Smith AM, Evans DM. Biomechanical assessment of a new type of flexor tendon repair. J Hand Surg Br. 2001, 26: 217–9.

Smith GH, Huntley JS, Anakwe RE, Wallace RJ, McEachan JE. Tensioning of Prolene reduces creep under cyclical load: relevance to a simple pre-operative manoeuvre. J Hand Surg Eur. 2012, 37: 823–5.

Strick MJ, Filan SL, Hile M, McKenzie C, Walsh WR, Tonkin MA. Adhesion formation after flexor tendon repair: a histologic and biomechanical comparison of 2- and 4-strand repairs in a chicken model. J Hand Surg Am. 2004, 29: 15–21.

Strickland JW, Glogovac SV. Digital function following flexor tendon repair in Zone II: A comparison of immobilization and controlled passive motion techniques. J Hand Surg Am. 1980, 5: 537–43.

Su BW, Protopsaltis TS, Koff MF et al. The biomechanical analysis of a tendon fixation device for flexor tendon repair. J Hand Surg Am. 2005a, 30: 237–45.

Su BW, Raia FJ, Quitkin HM et al. Gross and histological analysis of healing after dog flexor tendon repair with the Teno Fix device. J Hand Surg Br. 2006, 31: 524–9.

Su BW, Solomons M, Barrow A et al. Device for zone-II flexor tendon repair. A multicenter, randomized, blinded, clinical trial. J Bone Joint Surg Am. 2005b, 87: 923–35.

Takeuchi N, Mitsuyasu H, Hotokezaka S, Miura H, Higaki H, Iwamoto Y. Strength enhancement of the interlocking mechanism in cross-stitch peripheral sutures for flexor tendon repair: biomechanical comparisons by cyclic loading. J Hand Surg Eur. 2010, 35: 46–50.

Takeuchi N, Mitsuyasu H, Kikuchi K, Shimoto T, Higaki H, Iwamoto Y. The biomechanical assessment of gap formation after flexor tendon repair using partial interlocking cross-stitch peripheral sutures. J Hand Surg Eur. 2011, 36: 584–9.

Tan J, Tang JB. Locking repairs for obliquely cut tendons: Effects of suture purchase and directions of locking circles. J Hand Surg Am. 2004, 29: 891–7.

Tan J, Wang B, Xu Y, Tang JB. Effects of direction of tendon lacerations on strength of tendon repairs. J Hand Surg Am. 2003, 28: 237–42.

Tanaka T, Amadio PC, Zhao C, Zobitz ME, An KN. The effect of partial A2 pulley excision on gliding resistance and pulley strength *in vitro*. J Hand Surg Am. 2004a, 29: 877–83.

Tanaka T, Amadio PC, Zhao C, Zobitz ME, Yang C, An KN. Gliding characteristics and gap formation for locking and grasping tendon repairs: a biomechanical study in a human cadaver model. J Hand Surg Am. 2004b, 29: 6–14.

Tang JB. Indications, methods, postoperative motion and outcome evaluation of primary flexor tendon repairs in Zone 2. J Hand Surg Eur. 2007, 2: 118–29.

Tang JB. Outcomes and evaluation of flexor tendon repair. Hand Clin. 2013, 29: 251–9.

Tang JB. The future of flexor tendon surgery. In: Diao E, Mass DP (Eds.). *Tendon injuries in the hand and upper extremity: A master skills publication*. Rosemont, Illinois: American Society for Surgery of the Hand, 2011: 221–9.

Tang JB, Amadio PC, Boyer MI et al. Current practice of primary flexor tendon repair: A global view. Hand Clin. 2013a, 29: 179–89.

Tang JB, Cao Y, Xie RG. Effects of tension direction on strength of tendon repair. J Hand Surg Am. 2001, 26: 1105–10.

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Tang JB, Shi D, Gu YQ, Chen JC, Zhou B. Double and multiple looped suture tendon repair. J Hand Surg Br. 1994, 19: 699–703.

Tang JB, Tan J, Xu Y. Lengthening and locking: two ways to improve repair strength of obliquely lacerated tendons. J Hand Surg Am. 2003a, 28: 832–7.

Tang JB, Xie RG, Cao Y, Ke ZS, Xu Y. A2 pulley incision or one slip of the superficialis improves flexor tendon repairs. Clin Orthop Relat Res. 2007, 456: 121–7.

Tang JB, Xu Y, Chen F. Impact of flexor digitorum superficialis on gliding function of the flexor digitorum profundus according to regions in zone II. J Hand Surg Am. 2003b, 28: 838–44.

Tang JB, Xu Y, Wang B. Repair strength of tendons of varying gliding curvature: a study in a curvilinear model. J Hand Surg Am. 2003c, 28: 243–9.

Tang JB, Zhang Y, Cao Y, Xie RG. Core suture purchase affects strength of tendon repairs. J Hand Surg Am. 2005, 30: 1262–6.

Tang YQ, Mao WF, Wu YF. A new and accurate method to quantify gap formation in tendon repairs. J Hand Surg Eur. 2013b, 38: 808–9.

Taras JS, Raphael JS, Marczyk SC, Bauerle WB. Evaluation of suture caliber in flexor tendon repair. J Hand Surg Am. 2001, 26: 1100–4.

Vanhees M, Thoreson AR, Larson DR, Amadio PC, An KN, Zhao C. The effect of suture preloading on the force to failure and gap formation after flexor tendon repair. J Hand Surg Am. 2013, 38: 56–61.

Vigler M, Palti R, Goldstein R, Patel VP, Nasser P, Lee SK. Biomechanical study of cross-locked cruciate versus Strickland flexor tendon repair. J Hand Surg Am. 2008, 33: 1826–33.

Vizesi F, Jones C, Lotz N, Gianoutsos M, Walsh WR. Stress relaxation and creep: viscoelastic properties of common suture materials used for flexor tendon repair. J Hand Surg Am. 2008, 33: 241–6.

Wada A, Kubota H, Akiyama T, Hatanaka H, Miura H, Iwamoto Y. Effect of absorbable polydioxanone flexor tendon repair and restricted active mobilization in a canine model. J Hand Surg Am. 2001, 26: 398–406.

Wada A, Kubota H, Hatanaka H, Hotokezaka S, Miura H, Iwamoto Y. The mechanical properties of locking and grasping suture loop configurations in four-strand core suture techniques. J Hand Surg Br. 2000, 25: 548–51.

Wada A, Kubota H, Taketa M, Miuri H, Iwamoto Y. Comparison of the mechanical propertiesofpolyglycolide-trimethylene carbonate (Maxon) and polydioxanone sutures (PDS2) used for flexor tendon repair and active mobilization. J Hand Surg Br. 2002, 27: 329–32.

Waitayawinyu T, Martineau PA, Luria S, Hanel DP, Trumble TE. Comparative biomechanic study of flexor tendon repair using FiberWire. J Hand Surg Am. 2008, 33: 701–8.

Walbeehm ET, De Wit T, Hovius SE, McGrouther DA. Influence of core suture geometry on tendon deformation and gap formation in porcine flexor tendons. J Hand Surg Eur. 2009, 34: 190–5.

Wang B, Xie RG, Tang JB. Biomechanical analysis of a modification of Tang method of tendon repair. J Hand Surg Br. 2003, 28: 347–50.

Wit TD, Walbeehm ET, Hovius SE, McGrouther DA. The mechanical interaction between three geometric types of nylon core suture and a running epitenon suture in repair of porcine flexor tendons. J Hand Surg Eur. 2013, 38: 788–94.

Wolfe SW, Willis AA, Campbell D, Clabeaux J, Wright TM. Biomechanic comparison of the Teno Fix tendon repair device with the cruciate and modified Kessler techniques. J Hand Surg Am. 2007, 32: 356–66.

Wu YF, Cao Y, Zhou YL, Tang JB. Biomechanical comparisons of four-strand tendon repairs with double-stranded sutures: effects of different locks and suture geometry. J Hand Surg Eur. 2011, 36: 34–9.

Wu YF, Tang JB. How much does a Pennington lock add to strength of a tendon repair? J Hand Surg Eur. 2011, 36: 476–84.

Wu YF, Tang JB. Effects of tension across the tendon repair site on tendon gap and ultimate strength. J Hand Surg Am. 2012, 37: 906–12.

Wu YF, Zhou YL, Tang JB. Relative contribution of tissue oedema and the presence of an A2 pulley to resistance to flexor tendon movement: an *in vitro* and *in vivo* study. J Hand Surg Eur. 2012, 37: 310–5.

Xie RG, Tang JB. Investigation of locking configurations for tendon repair. J Hand Surg Am. 2005, 30: 461–5.

Xie RG, Xue HG, Gu JH, Tan J, Tang JB. Effects of locking area on strength of 2- and 4-strand locking tendon repairs. J Hand Surg Am. 2005, 30: 455–60.

Xu Y, Tang JB. Effects of superficialis tendon repairs on lacerated profundus tendons within or proximal to the A2 pulley: an in vivo study in chickens. J Hand Surg Am. 2003, 28: 994–1001.

Zeplin PH, Zahn RK, Meffert RH, Schmidt K. Biomechanical evaluation of flexor tendon repair using barbed suture material: a comparative ex vivo study. J Hand Surg Am. 2011, 36: 446–9.

Zhao C, Amadio PC, Zobitz ME, An KN. Resection of the flexor digitorum superficialis reduces gliding resistance after zone II flexor digitorum profundus repair *in vitro*. J Hand Surg Am. 2002, 27: 316–21.

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