FLEXOR TENDON REPAIR IN FINGERS: SUTURE TECHNIQUE, POSTOPERATIVE REHABILITATION AND PREDICTORS OF OUTCOME

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TO MY FAMILY
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ABBREVIATIONS

ADL – Acquired daily living
AROM – Active range of motion
95% CI – 95% confidence interval
CPM – Controlled passive mobilization
DIP joint – Distal interphalangeal joint
EAM – Early active mobilization
FDP – Flexor digitorum profundus
FDS – Flexor digitorum superficialis
FPL – Flexor pollicis longus
FW – FiberWire
IP joint – Interphalangeal joint
MCP joint – Metacarpophalangeal joint
OR – Odds ratio
PAH – Place and hold
PAP – Palmar aponeurosis pulley
PIP joint – Proximal interphalangeal joint
POS – Pull-out suture
RCT – Randomized controlled trial
ROM – Range of motion
SD – Standard deviation
TILT – Transverse intraosseous loop technique
VAS – Visual analogue scale
LIST OF PAPERS

This thesis is based on the following papers:


GENERAL INTRODUCTION

Importance of flexor tendon injuries

Intact flexor tendons are the prerequisite for normal use of the human hand; they make us able to perform both power grip and fine motoric activities. A relatively small injury can lead to disruption of these tendons; the consequences will be a lack of ability to actively bend the fingers and thus a compromised hand function. A recent study from the Mayo Clinic, Rochester, USA showed a 33/100,000 incidence of flexor tendon injuries in a mixed rural and urban population (de Jong et al., 2014). The treatment of these injuries is challenging and the functional results are not always optimal; excellent or good function can be expected in approximately 80% of the cases (Elliot, 2002, Tang, 2013). Ruptures or adhesions around the repaired tendon needing tenolysis are found in approximately 5% each (Elliot, 2002, Dy et al., 2012b), and further surgery is required in around 6% of the cases (Dy et al., 2012a). The recommended period of hand protection after flexor tendon repair is up to 10-12 weeks; however, we do not have enough evidence about the length of the healing process (Adolfsson et al., 1996). Although flexor tendon injuries constitute less than 1% of hand traumas, they affect mostly young, active and working people (Hill et al., 1998). Flexor tendon injuries entail significant social and economic burdens for the patient, the health care and the society. According to the calculations of Rosberg et al. (2003) the mean cost of the treatment of a flexor tendon injury in Sweden was 48,500 SEK (5,255 €) for the health-care system and further 93,000 SEK (10,076 €) for the community included sick leave, loss of production and tax incomes. The controversy of how to decrease complications and improve the outcome of flexor tendon repair has caused a debate probably more extensive than any other topic in hand surgery (Tang, 2007). The many investigations on the topic over the last decades have shown improved results due to advances in surgical technique and rehabilitation (Wu and Tang, 2014); however, consensus on the best method of repair or rehabilitation has not been achieved (Elliot, 2002, Pettengill, 2005, Tang, 2007, Chesney et al., 2011). We still have much to learn.
Anatomy and physiology

The anatomy of the flexor tendons of the fingers is complex (Figure 1). The tendons contain fibroblasts and an extracellular matrix consisting of approximately 68% water, 30% collagen type I fibres, 2% elastin and proteoglycans. The longitudinally arranged collagen fibres provide the strength, whereas the elastin gives flexibility to the tendons. The flexor muscles originate from the medial humerus epicondyle and their tendons extend to the fingers. They transmit force from the muscle bellies to the phalanges, providing strength and motion to the fingers and wrist. The flexor tendons are located on the palmar aspect of the distal forearm and run through the carpal tunnel in two layers. The deep layer consists of the flexor digitorum profundus (FDP) tendons, inserting on the base of the distal phalanges. The flexor digitorum superficialis (FDS) tendons run superficial to the former until the level of the metacarpophalangeal (MCP) joints, where the tendons split into two lateral slips surrounding the FDP tendons (bifurcation). The two slips meet again underneath the FDP tendons forming the Camper’s chiasma before inserting on the bases of the middle phalanges. The FDP and the FDS tendons are the primary flexors of the distal interphalangeal (DIP) and the proximal interphalangeal (PIP) joints, respectively; both are secondary flexors of all other proximal joints they cross. The thumb has one long flexor tendon inserting on the distal phalanx, the flexor pollicis longus (FPL), which also runs through the carpal tunnel (Singh et al., 2015).

Figure 1. Anatomy of flexor tendons in the fingers. Blood supply to the tendons through the vinculum system. (Courtesy of Prof. Dr Martin Franz Langer)
The tendons are surrounded by loose synovial tissue in the carpal tunnel and become enclosed within tight synovial sheaths distal to the MCP joints. The main function is lubrication, reducing friction and improving gliding during finger flexion. The synovial fluid has an important role in nutrition of the tendon as well, complementing the blood supply passing through the vinculum system. The vessels lie mostly in the dorsal half of the tendon and are orientated longitudinally.

The tendons are running in fibro-osseous canals along the fingers where the skeleton forms the dorsal wall and the tendon sheath provides palmar coverage. The tendon sheath is segmentally thickened to form annular and cruciform pulleys, which keep the tendons close to the bone during flexion (Figure 2). There are five annular pulleys numbered in ascending order from proximal to distal (A1-A5) and three cruciform pulleys (C1-C3). The A1, A3 and A5 pulleys are located over the MCP, PIP and DIP joints, respectively. The A2 and A4 pulleys are the longest and are located over the middle part of the proximal and distal phalanx, respectively. The A2 and A4 pulleys are considered to be the biomechanically strongest and the most important to prevent tendon bowstringing (Singh et al., 2015). The anatomy of the tendon sheath in the thumb is not so constant. There are usually two annular pulleys (A1 and A2) located over the MCP and IP joints, and the oblique pulley over the basal phalanx, running in the direction from proximally ulnar to distally radial. Newer investigations have identified an accessory pulley between the A1 and the oblique pulleys called the variable annular (vA) pulley, with some variations in location and thickness (Schubert et al, 2012).

**Figure 2.** Anatomy of the fibro-osseous tendon sheath; the relation of the subzones with the pulley system. (Courtesy of Prof. Dr Martin Franz Langer)
The course of the flexor tendons is divided into five anatomic zones (Figure 3). Zone 1 represents the region distal to the insertion of the FDS, where the FDP tendon lies alone within the sheath. Zone 2 describes the region from the proximal end of the A1 pulley to the insertion of the FDS tendon on the middle phalanx. This is the location where the FDP tendon pierces the FDS tendon proximal to the chiasma; the two tendons share the fibro-osseous sheath of the digit. Zone 2 is the most problematic area to treat and this zone was earlier referred to as “no man’s land”. Zone 3 lies between the distal part of the transverse carpal ligament and the A1 pulley, and comprises the extrasynovial part of the tendons with the origin of the lumbrical muscles from the FDP tendons and the area of the palmar aponeurosis pulley (PAP) system (Langer et al., 2015b). Zone 4 is located within the carpal tunnel where FPL and all FDP and FDS tendons run in near relation to the median nerve. Zone 5 is located proximal to the carpal tunnel and represents the musculo-tendinous junctions (Singh et al., 2015).

Figure 3. Zones of flexor tendons according to International Federation of Societies for Surgery of the Hand (IFSSH)
The zones are further divided into subzones based on the relation to the main pulleys (Figure 2) (Moiemen and Elliot, 2000, Tang, 1994). Subzone 1a is located distal to the A5 pulley. In case of injury to this site, there is no distal FDP tendon stump feasible for direct suture and the tendon needs reattachment to the distal phalanx. Subzone 1b lies under the C3 and A5 pulleys, and subzone 1c under the tight A4 pulley, but distal to the FDS insertion. Subzone 2a is located under C2 and the proximal part of A4; the FDS stump is too short for direct tendon suture and reattachment is necessary. Subzone 2b is under the C1 and A3 pulleys; the tendon sheath is not very tight and the FDS chiasma lies under the FDP tendon. The area of the A2 pulley is the subzone 2c; the tightest part of the sheath where the FDS tendon is flat and divides into two slips. Subzone 2d is located proximal to the A2 and under the A1 pulley; the shape of the FDS tendon becomes similar to the FDP tendon.

The anatomy of the tendon sheath in the thumb is different. The FPL tendon is surrounded by a continuous synovial sheath from the carpal tunnel to the distal insertion, often referred to as the radial bursa. Zone 4 and 5 correspond to the fingers. Zone T3 is the area of the thenar muscles. Zone T2 is the area within the fibro-osseous canal under the pulleys; this is the problematic region of the thumb. Zone T1 is located distal to the A2 pulley and represents the insertion on the distal phalanx.

**Mechanism of flexor tendon injuries**

Dissections of the flexor tendons usually occur in conjunction with open injuries; cuts or stab injuries to the hand. According to Rosberg et al. (2003) 40% of all flexor tendon injuries occurred at home, 30% of the injuries were work related and 27% occurred in leisure time. The most common mechanism of injury was a cut by a knife (46%), broken glass (26%) or a metal object (19%), but injury from motorized tools has become more frequent, as such machines are now widely available for home use. Closed ruptures can also occur, especially in contact sports (Netscher and Badal, 2014). The FDP and the FDS tendons can be injured alone; however, both tendons are often cut simultaneously. Tendon injuries are often combined with digital nerve or joint capsule injuries. In zone 4 and 5 multiple tendon injuries are often associated with injuries of the
median or ulnar nerve and the arteries, which may significantly compromise the functional recovery.

**Tendon healing**

The natural healing process of the tendons is slow due to their hypocellular and hypovascular nature. Even after 1 year, the structure and function of the resulting tissue remain inferior to uninjured tendons. The first stage of the healing process is the inflammatory response. A blood clot forms at the site of injury and inflammatory cells are attracted by the different biological factors released. Necrotic debris is cleaned by phagocytosis. The second stage, known as the proliferative or reparative phase, begins roughly on the second day after the injury. Fibroblasts migrate to the site of injury from the surrounding tissue (extrinsic mechanism), and tenocytes in the tendon begin to proliferate (intrinsic mechanism). The synthesis of extracellular matrix starts at this stage. The newly formed matrix contains more water than the mature matrix due to the increased amounts of collagen type III and glycosaminoglycan. The third stage, the remodelling phase, starts 1–2 months after the injury. Tenocytes and collagen fibres become more and more aligned in the direction of mechanical stress, and the proportion of collagen type I increases. After approximately 10 weeks the fibrous scar gradually resembles normal tendon tissue. The process continues for years, and the healed tendon never completely regains the biomechanical properties and ultrastructural characteristics of the intact tendon (Yang et al., 2013).

Cut or ruptured flexor tendons do not heal spontaneously. The proximal stumps of the tendons retract due to the muscular tone, and the stumps will no longer be in contact without surgical intervention. Healing after flexor tendon repair can be achieved with immobilization of the finger. It facilitates the extrinsic healing mechanism resulting in adhesions between the tendon and the synovial sheath. Keeping the tendon in motion under the healing process can hinder the tissue ingrowth and facilitate intrinsic healing, but the strain should not exceed the holding capacity of the repaired tendon. On the other hand, there is experimental evidence showing that mechanical stress induces tenogenesis and increases the strength of the healing tendon. It is accepted that healing
tendon tissue should be loaded in a controlled manner to promote favourable remodelling (Yang et al., 2013).

**Repair of flexor tendon injuries**

In the treatment of flexor tendon injuries, the goal is not only to achieve tissue healing, but also to restore tendon gliding and finger function.

Nicoladini (1880) performed the first flexor tendon repair with a transverse suture component and grasping of the tendon fibres. Since then several different suture configurations have been tried; however, the results were often disappointing. Bunnell postulated the tendon sheath area of the finger as “no man’s land”. He recommended entirely removal of the injured flexor tendon and immediate replacement with tendon graft instead of suture (Bunnell, 1918). Although Harmer and Kirchmayr independently recognized the advantage of primary repair already in 1917, it didn’t become popular until the late 1950s because of the Bunnell teaching. In the 1960s, thanks to Kleinert’s and Kessler’s work (Kleinert et al., 1967, Kessler and Nissim, 1969), direct repair and early mobilization became the standard method for treatment of flexor tendon injuries. Since then many papers have recommended different suture types and materials (Figure 4), without any agreement on the best method for flexor tendon repair (Langer et al., 2015a). David Elliot’s words are still applicable: “At the time of writing, there is no ‘best’ suture material or ‘best’ suture technique and the choice of each in any one unit, country or area of the world is more often determined by opinion, historical precedence and availability of particular materials than by science” (Elliot, 2002).

The classical Kessler suture (Kessler and Nissim, 1969) has been revised several times (Pennington, 1979, Tajima, 1984, Strickland, 1989), and the term modified Kessler repair covers an inhomogeneous group of two-strand core suture methods. This type of tendon suture combined with passive finger flexion by rubber band traction became the golden standard in most hand surgical centres in the 1980s. As more aggressive mobilization regimes became increasingly popular, there was a need for stronger repair techniques.

Progress in tendon repair has been achieved steadily over the past decade and several tactics were aiming to improve the strength of the repaired tendon. It is widely
accepted that increasing the number of sutures crossing the repair site improves the biomechanical properties proportionally. Multi-strand core sutures became the new standard in many hand centres. There are alternative ways to achieve a stronger suture: locking loop configuration instead of grasping loops, increased suture purchase, stronger suture material, larger suture diameter, pretensioning the suture and complex epitendinous suture configurations. (Wu and Tang, 2014). The usual problems with very complex repair methods are the bulkiness and the increased friction. There is no consensus on the best method of repair, but an ideal repair should provide adequate strength to prevent gap formation and failure, cause minimal tendon damage and tissue reaction, not increase gliding resistance and be easy to perform.

In addition to the direct suture, other treatment modalities have been investigated such as scaffold augmentation, surface modification, tissue engineering, cell therapy, application of bioactive molecules and biophysical stimulation. Despite intensive research activity on these topics, little clinical evidence exists except for the controlled
mobilization, which is a type of biophysical stimulation. None of the other regenerative medicine approaches has been implemented in human clinical trials or clinical practice to date (Sammer and Chung, 2014, Yang et al., 2013).

**Tendon reattachment**

FDP tendon avulsion injuries and divisions in zone 1a-1b with a distal stump insufficient for placing a conventional suture need reattachment directly onto the distal phalanx. The pull-out suture (POS, Figure 5) originally described by Bunnell (1940) and its several modifications has been widely used to reattach the tendon with metal wires or sutures tied over a button on the nail or the fingertip (Wilson and Sammut, 2003). The method is functional, but may be associated with complications: infection, rupture of the repair, loosening of the suture wire or the button, catching in clothes, nail bed damage, skin necrosis and discomfort during removal. The use of bone suture anchors or other forms of internal transosseous fixation may reduce the risk of the above-mentioned complications, but the problems are difficulties with adjusting the tension, inapplicability to growing skeleton and high technical demand. Techniques with a transverse intraosseous drill hole through the distal phalanx are supposed to overcome these limitations (Sood and Elliot, 1996, Tripathi et al., 2009).

![Figure 5. Reinsertion of avulsed FDP tendon with pull-out suture, tied over a button on the nail.](image)
Rehabilitation

If the finger is immobilized until healing of the tendon occurs, the tendon will adhere to the surrounding tissue, and the finger becomes stiff. It is now accepted that proper postoperative rehabilitation is equally important for the functional results as the quality of the surgery. Keeping the repaired tendon in motion with careful postoperative management facilitates the intrinsic healing and minimizes adhesions, thus improving the gliding and the strength of the tendon. On the other hand, aggressive mobilization increases the risk of re-rupture. The rehabilitation should adjust to the strength of the surgical repair. However, sufficient evidence exists to favour early mobilization over immobilization, and the benefits are greatest when mobilization starts within the first week (Pettengill, 2005).

Because of the limited holding capacity of the traditional modified Kessler sutures, passive flexion exercises have been used to keep the tendon in movement during the healing process. Passive finger flexion can be combined with active extension exercises, using a dynamic splint with rubber band (Figure 6) as described by Kleinert (Kleinert et al., 1967, Lister et al., 1977). Controlled passive flexion and extension described by Duran and Houser (1975) is another popular low strain rehabilitation. These controlled passive motion (CPM) protocols were subject to further investigations, and several modifications have been published (Pettengill, 2005, Chesney et al., 2011, Clancy and Mass, 2013).

Figure 6. Kleinert type dynamic splint, with rubber band attached to the nail of the injured finger.
Traditionally, the patients were not allowed to flex their operated fingers actively during the first four weeks. The protocols allowing immediate active flexion and extension of the fingers in a controlled manner were called early active mobilization (EAM). Active finger flexion has the theoretical advantages of larger tendon excursion, reduced bulkiness and oedema at the repair site, maintenance of the motor muscles and promotion of intrinsic tendon healing (Pettengill, 2005). The first papers with EAM protocols showed encouraging results (Cullen et al., 1989, Savage and Risitano, 1989, Small et al., 1989).


Others used “active hold” or “place and hold” (PAH) exercises, often in conjunction with dynamic splints (Silfverskiöld and May, 1994, Klein, 2003, Osada et al., 2006). According to PAH regimes, the fingers are passively flexed, and the patient attempts to hold this position with active contraction of the flexor muscles. This form of rehabilitation is also categorized as EAM; however, no true active finger flexion is performed.

Only few investigations compared EAM with CPM, most of those are retrospective case control studies (Bainbridge et al., 1994, Baktir et al., 1996, Peck et al., 1998, Hoffmann et al., 2008, Frueh et al., 2014). Two randomized controlled trials compared CPM with PAH (Trumble et al., 2010, Farzad et al., 2014). All these studies except one (Peck et al., 1998) suggest better results with the EAM protocol. However, the clinical evidence supporting superiority of EAM in contrast to CPM is insufficient; not even systematic reviews could conclude what was the best rehabilitation protocol (Thien et al., 2004, Chesney et al., 2011).

The difference between the groups in the comparative studies did not only comprise the mode of finger flexion (active or passive). There was at least one additional dissimilar factor in every case: the position of the wrist and the metacarpophalangeal (MCP) joints in the splint, the configuration of the splint, the use or abundance of rubber
bands, or different surgical technique. It remains unclear whether the active finger flexion itself or other factors caused the improved results of EAM.

**Outcome, complications and reoperations**

The outcome of flexor tendon injuries is often measured as the combined active range of motion (AROM) of the PIP and DIP joints, and is usually converted into functional gradings as excellent, good, satisfactory or poor (Strickland and Glogovac, 1980). Tang’s functional grading system includes the grade “failure”, when the AROM is less than 30% of the contralateral finger, but the tendon has not necessarily ruptured (Tang, 2013). Excellent or good function can be expected in approximately 80% of the cases (Elliot, 2002, Tang, 2013), implying approximately 20% suboptimal result. A recent meta-analysis found rates of reoperation of 6%, re-rupture of 4%, and adhesion formation of 4% (Dy et al., 2012a).

The first major concern is the formation of adhesions, leading to finger stiffness. This is common in conjunction with extrinsic healing mechanisms in immobilized tendons; however, insufficiently mobilized tendons can also become stuck within the sheath. A difference between the passive and active finger range of motion (ROM) can indicate tendon adhesions. Several months of intensive therapy can regain some function, but prevention is easier than treatment. Fingers with good passive ROM could benefit from surgical tenolysis. However, there is a significant risk of further complications with this operation: disruption of pulleys or the repaired tendon and injury to the neurovascular structures. When planning tenolysis one should be prepared, if necessary, to perform staged tendon grafting with silicon rod and pulley reconstruction as well (Pulos and Bozentka, 2015).

The second main concern is rupture of the repaired tendon. Repaired tendons are weakest between the postoperative days six and 12, with most ruptures reported around day 10. Weak suture material or poor repair can lead to mechanical failure, especially in combination with aggressive postoperative rehabilitation protocols. However, the majority of ruptures are a result of patient noncompliance, including removal of the splint, lifting heavy objects or attempting strong grasp (Harris et al., 1999). Ruptures occurring early after primary suture may be repaired directly. The results with re-suture
are, however, inferior compared with successful primary tendon repair: 51% excellent or
good result in a retrospective series (Dowd et al., 2006). In some cases, especially in the
little fingers and with intact FDS, one could accept the hand function without further
attempts to repair. Ruptures occurring more than 3 weeks postoperatively are less likely
to be successfully repaired and may require grafting or staged tendon reconstruction
(Pulos and Bozentka, 2015).

Contracture of the PIP joint is also a common complication, especially in
combination with the use of rubber bands. Opposite to adhesions, there is no difference
between passive and active ROM. It can result from scarring of the volar plate, tendon
bowstringing due to pulley disruption, concomitant fracture, collateral ligament injury,
skin contracture or poor local tissue nutrition due to neurovascular injury. It is important
to identify interphalangeal joint contractures early and start treatment with splinting of
the joint in extension between the therapy sessions and at night, in addition to active
extension exercises. Recalcitrant contractures can be considered for surgical joint release
4 to 6 months postoperatively (Pulos and Bozentka, 2015).

Pulley disruptions are manifested by flexor tendon bowstringing and secondary
loss of ROM. The increased lever arm and flexion momentum due to the bowstringing
may lead to a flexion contracture, while the increased linear excursion required for
angular movement may lead to a limitation in active flexion. The A2 and A4 pulleys are
the most critical for active digital flexion and should be considered for repair or
reconstruction. After secondary pulley reconstruction, one should support the flexor
tendon using the contralateral hand, a wooden block or an external ring during the
rehabilitation (Pulos and Bozentka, 2015).

Bulky tendon repairs or partial tendon injuries can be caught by the edge of the
main pulleys, causing triggering, or even rupture. Modern treatment strategies
recommend partial pulley release, without increasing the risk of bowstringing (Tang,
2007). In case of significant postoperative triggering, early reoperation with pulley release
is recommended to prevent rupture.

There are other, less common complications necessitating further interventions,
such as infections, suture granulomas, skin necrosis, hypertrophic scars and complex
regional pain syndrome; however, these are not specific for flexor tendon repair.
AIMS OF STUDY

1. To compare the biomechanical properties of a novel two-strand repair (Yotsumoto-Dona) with the traditional Kessler suture.

2. To prove that the novel two-strand repair (Yotsumoto-Dona) is strong enough to withstand the loads under early active mobilization.

3. To compare the functional outcome and the incidence of complications between a novel tendon reattachment method (Transverse intraosseous loop technique) and the traditional pull-out suture.

4. To identify the patient and injury specific predictors of the functional outcome after flexor tendon repair in the zones 1, 2 and 3.

5. To clarify the importance of several treatment-related factors aiming to improve the functional outcome after flexor tendon repair in the zones 1, 2 and 3.

6. To compare the functional outcome of early active mobilization with controlled passive mobilization after flexor tendon repair in the zones 1, 2 and 3.
Eighteen fresh-frozen porcine flexor tendons were randomly divided into two groups and cut sharply at a level corresponding to zone 2. Three surgeons repaired the tendons under loupe magnification with two different two-strand methods. Nine tendons (Kessler group) were repaired with grasping type modified Kessler suture using 3-0 monofilament nylon. A simple running peripheral suture with 5-0 monofilament nylon was added. The other nine tendons (Yotsumoto-Dona group) were repaired with side-locking loop suture using 3-0 braided polyblend polyethylene (FiberWire (FW), Arthrex Co., Naples, FL, USA) combined with a 5-0 monofilament nylon interlocking horizontal mattress peripheral suture (Figure 7) (Yotsumoto et al., 2005, Dona et al., 2003). The horizontal component of the core sutures was placed 10 mm from the cut ends, and the knots were tied with one surgeon’s and four square knots between the cut ends.

The specimens were secured in custom-made clamps and tested linearly to failure using a servo hydraulic material-testing machine (Figure 8). From the load-displacement curves, we defined the yield and ultimate force, energy to yield, energy to failure and stiffness of the suture. Five intact tendons were also tested with the same apparatus and
a mean load displacement curve was calculated as the reference curve for the uninjured tendon. Using this reference curve, we calculated the 2 mm gap force for each specimen. The statistical analyses were carried out with Mann-Whitney U test; probabilities of less than 0.05 were accepted as significant.

![Image](image.jpg)

**Figure 8.** The specimens were secured in custom-made clamps and tested linearly to failure using a servo hydraulic material testing machine (MTS 858 Mini Bionix, MTS System Corporation, Minneapolis, MN, USA).

The 2 mm gap force, yield force, ultimate force, stiffness, energy to yield, and energy to failure were all significantly higher in the Yotsumoto-Dona group than in the Kessler group (Table 1). All Yotsumoto-Dona specimens performed a yield force exceeding 35 N while in the Kessler group only four did. The yielding rate was 6/9 in the Kessler and 2/9 in the Yotsumoto-Dona group. The six Kessler repairs underwent yield when the sutures began to pull out. Finally, all the core sutures failed when the knot broke in all the modified Kessler and six of the Yotsumoto-Dona repairs; in three of the latter the knots had loosened leading to yield in two of them. All the simple running epitendinous sutures failed by pulling out; in one specimen, it broke as well. Three interlocking horizontal
mattress sutures failed because they broke at the intersections of the threads, and the remaining six predominantly pulled out, but the sutures were also torn in five of them (Figure 9).

**Table 1.** Biomechanical properties of the modified Kessler and Yotsumoto-Dona groups. Data are median (interquartile range).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Modified Kessler</th>
<th>Yotsumoto-Dona</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 mm gap force (N)</td>
<td>25.8 (12.2-28.1)</td>
<td>30.9 (28.1-39.5)</td>
<td>0.005</td>
</tr>
<tr>
<td>Yield force (N)</td>
<td>35 (24.6-54.4)</td>
<td>82.7 (64.9-114.1)</td>
<td>0.003</td>
</tr>
<tr>
<td>Ultimate force (N)</td>
<td>50.9 (34.4-55.1)</td>
<td>82.7 (76.6-114.1)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Stiffness (N/mm)</td>
<td>7 (5.8-9.1)</td>
<td>12.5 (10-14.5)</td>
<td>0.001</td>
</tr>
<tr>
<td>Energy to yield (J)</td>
<td>0.09 (0.06-0.18)</td>
<td>0.45 (0.2-0.5)</td>
<td>0.004</td>
</tr>
<tr>
<td>Energy to failure (J)</td>
<td>0.21 (0.18-0.28)</td>
<td>0.45 (0.35-0.5)</td>
<td>0.001</td>
</tr>
<tr>
<td>Yielding rate</td>
<td>6/9</td>
<td>2/9</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Figure 9.** Failure mechanism in the two groups. (A) Modified Kessler group: breakage at the knot of all core sutures and pull out of all simple running sutures. (B) Yotsumoto-Dona group: breakage at the knot in six and knot loosening in three core sutures. Three interlocking horizontal mattress sutures broke at the intersections and six predominantly pulled out, but the sutures were torn in five of them.
In this study we found that the relatively easy to perform Yotsumoto-Dona tendon repair was biomechanically superior to the modified Kessler suture, and it might withstand the loads occurring during early active mobilization, whereas the modified Kessler suture can probably not.

**Paper 2**

We compared the results of two different methods of tendon reattachment in a retrospective analysis. Forty adult patients operated between January 2005 and May 2010 with delayed primary repair of zone 1a flexor tendon lesions in the fingers were included. Replantation, revascularization, postoperative immobilization, severe DIP joint injuries of the fingers and dropout from the follow-up were exclusion criteria. The choice of technique was the surgeon’s preference.

Thirty-five tendons of 29 patients were reattached with the classical pull-out suture (POS). In this technique a 4-0 stainless steel suture was placed in the tendon in a modified Kessler pattern. Then the wires were passed through the distal phalanx and tied over a plastic button on the nail. The pull-out wire was passed proximally, penetrating the skin proximal to the DIP joint crease.

Thirteen tendons of 11 patients were repaired with the “Transverse Intraosseous Loop Technique” (TILT, Tripathi et al., 2009, Azzopardi and Iyer, 2009). An intraosseous tunnel was drilled through the basis of the distal phalanx. A side-locking 3-0 FW loop suture (Yotsumoto et al., 2005) was placed in the tendon and the needle of the suture was passed through the bone canal and back into the palmar wound. The suture was tied burying the knot at the repair site between the tendon and the distal phalanx, or between ends of the tendon in case of a very short distal stump (Figure 10).

![Figure 10](image)  
*Figure 10.* Schematic drawing of the transverse intraosseous loop technique (TILT). The FDP tendon is reattached through a bone canal. The knot is buried underneath the tendon stump.
After closure of the wound, all patients were equipped with a Kleinert type dynamic splint with rubber band traction on the injured fingers. Active extension – passive flexion exercises began on the first postoperative day. All patients in the POS group and four in the TILT group followed this rehabilitation protocol; seven in the TILT group were allowed un-resisted active finger flexion in addition. At 4 weeks the splints were removed and all patients began active exercises. The pull-out wires were removed on an outpatient basis during the fifth postoperative week. Except for more dominant hand injuries in the POS group the groups did not differ significantly regarding age, gender, smoking, side, multiple finger injuries, the finger injured, the degree of soft tissue damage, associated injuries and delay of surgery.

The mean follow-ups were 8 (range 2-35) and 6 (range 2-12) months in the POS and the TILT group, respectively. The mean (SD) PIP + DIP AROM were 101 (34) and 125 (36) degrees at 8 weeks; 123 (28) and 138 (22) degrees at the last follow up in the two groups, respectively. Analysed with Student T-test, only the difference at 8 weeks was statistically significant (p= 0.049 at 8 weeks and p=0.056 at the last follow up).

According to Strickland and Glogovac (1980), "excellent" or "good" functional gradings were found in 11/35 and 9/13 fingers at 8 weeks, and in 20/35 and 10/13 at the last follow up of the POS and TILT groups, respectively. Analysed with Fisher’s exact test, only the difference at 8 weeks was statistically significant (p=0.023 at 8 weeks and p=0.202 at the last follow up). Multiple logistic regression analyses showed better functional result using TILT both at 8 weeks and at the last follow up, the former difference was statistically significant (p=0.03; OR=12; 95 %CI 1.2; 110 and p=0.18; OR=3.5; 95%CI 0.55; 22, respectively).

Ten patients in the POS group experienced 12 complications: four superficial infections were cured with per oral antibiotics; one of them developed rupture of the repair. One significant PIP and one DIP joint contracture, one adhesion, two granulomas, one nail deformity and one postoperative carpal tunnel syndrome were recorded. Four patients were reoperated: one carpal tunnel release, one teno-arthrolysis and two resections of granulomas. There was no complication and no reoperation in the TILT group. The different incidence of complications was statistically significant (p=0.02), while the difference in reoperations was insignificant (p=0.56).
In this study, we found superior functional results with TILT compared to POS for FDS tendon reattachments. TILT is safe; it had fewer complications and avoided the soft tissue and nail problems associated with POS. Our results suggest that TILT may be preferable to POS for zone 1a tendon repairs.

Paper 3

We retrospectively reviewed the outcomes of flexor tendon repairs in zones 1, 2 and 3 in patients operated in Rikshospitalet, Oslo University Hospital between January 2005 and May 2010. After exclusion of thumb injuries, zone 4 and 5 injuries, reattachments, replantations, revascularizations, repairs needing post-operative immobilization, partial FDP lacerations, referrals from other hospitals and patients with insufficient documentation or follow up, 291 patients with 356 injured fingers were included. Fingers with crush injuries were also included if tendon repair was possible and followed by early mobilization.

The following variables were recorded for each case: age, gender, smoking, comorbidity, side, injured finger, single or multiple finger injury, zone and subzone of injury, extent of soft tissue damage, associated injuries, extent of FDS injury, delay of surgery, surgeon’s experience, FDP suture technique, suture material, type of rehabilitation, treatment of tendon sheath/pulley system, and treatment of FDS tendon. The AROM measures were collected from the therapists’ notes, the reoperations from the medical documentation. The post-operative 8 weeks’ and the last PIP + DIP AROM measures with a mean follow up of 7 (range 3-98) months were registered.

Multiple linear regression analyses were performed in six series after allocating the fingers into the following groups: all zones, pooled zone 1 and 2 injuries for assessment of the effect of the tendon sheath and pulley treatment, and pooled zone 2 and 3 injuries for assessment of the variables associated with the FDS tendon. AROMs at 8 weeks and at the last follow up were chosen as dependent variables. To gain the best model fit, some variables with insignificant effect (p>=0.05) were kept as well. Some multinomial categorical variables were merged into binary “dummy variables”. We excluded comorbidity as an explanatory variable because of the strong collinearity with
smoking, and the suture material because of the large proportion of missing data and the excessive collinearity with repair technique.

Three hundred and thirty-two fingers were available for functional analysis at 8 weeks and 225 had a minimum of 3 months follow up. The mean (SD) AROM was 98 (40) and 114 (45) degrees at 8 weeks and at the last follow up, respectively. “Excellent” or “good” function according to Strickland and Glogovac (1980) was achieved in 95 (29%) and 107 (48%) fingers at 8 weeks and at the last follow up, respectively. Fifteen digits (4%) suffered rupture of the repair, four during the first four weeks while still using the splint, seven within 2 weeks after removal of the splint and four after more than 6 weeks post-operatively. Forty-eight (13%) of 356 fingers required revision surgery including 15 (4%) re-repairs of ruptured tendons, 14 (4%) tenolyses including two joint releases, eight (2%) tenodeses or arthrodeses, five (1%) corrections of finger scars, five (1%) excisions of granulomas, two carpal tunnel releases and one amputation. Four fingers underwent more than one reoperation.

Significant regression equations were found in all models; however, the adjusted R squared values of the models were relatively low; e.g. adjusted R squared of 0.227 in model 1 means that the model can explain 22.7% of the deviations from the expected values.

Assessing all zones, age, smoking, injury localization between subzone 1c and 2c, associated fracture and using traditional Kessler or double-Kessler suture instead of Yotsumoto-Dona suture were the significant negative predictors for AROM at both 8 weeks and at the last evaluation. These variables were significant predictors in all subgroup analyses as well. The delay of surgery had no significant effect; however, inclusion into the analyses as a predictor improved the statistical model (Figure 11). The predicted final AROM was 163 degrees. Yotsumoto-Dona suture increased the AROM with 36 degrees; associated fracture, injury localization between subzone 1c and 2c and smoking decreased with 34, 29 and 29 degrees, respectively. The final AROM decreased 0.7 degrees for each year of age and 0.3 degrees for each day of delay. These are relatively small effects, nevertheless representing a reduction of 35 degrees in a fifty-year-old patient, and a further 4 degrees of reduction at 14 days of delay. The AROM at the last evaluation correlated significantly with the 8 weeks’ results.
In the subgroup analysis of zone 1 and 2 injuries, suture or preservation of the tendon sheath/pulley was an additional significant negative predictor. Injury of the little finger and the use of Kleinert’s rehabilitation instead of EAM were insignificant predictors for the 8 weeks’ AROM, implying 15, 9 and 20 degrees of reduction, respectively. Assessing the late results, both the double Kessler repair and the Yotsumoto-Dona technique outperformed traditional Kessler suture. The treatment of the sheath-pulley system and the rehabilitation could no longer be included in the statistical model, probably due to the smaller sample size.

Figure 11. Predictors of AROM at the final evaluation, assessing all zones. Error bars represent 95% confidence interval of the mean. (A) Significant negative correlation between age and AROM. (B) Significant negative effect of smoking. (C) Significant negative effect of injury localization between subzones 1c and 2c. (D) Significant negative effect of an associated fracture. (E) Significant negative effect of modified Kessler repair.
Assessing the 8 weeks’ AROM of the pooled zone 2 and 3 injuries, the condition of the FDS tendon was an additional significant predictor. Repaired and unrepaired total FDS tendon injuries decreased the AROM with 9 and 18 degrees, respectively, compared to the uninjured FDS. It was also an insignificant predictor of the late results; double Kessler and Yotsumoto-Dona sutures were both superior to Kessler suture. The extent of soft tissue damage was an insignificant predictor for both the 8 weeks’ and the late AROM.

Our statistical analysis was unable to show any effect of gender, side, single or multiple finger injuries, association with other injuries than fractures, extent of superficial tendon damage or surgeon’s experience on the functional results.

We can summarize, that increasing age, smoking, injury localization between subzones 1c and 2c, injury of the little finger, the extent of soft tissue damage, concomitant skeletal injury, delay of surgery, repair technique, treatment of the tendon sheath/pulley system, treatment of the concomitant superficial flexor tendon injuries and the type of rehabilitation were found to be predictors of the functional results after flexor tendon repair in zones 1, 2 and 3 in our material.

**Paper 4**

We evaluated the effect of active finger flexion after flexor tendon repair in a prospective randomized controlled study, where the groups differed only by allowing active finger flexion or not.

We included patients referred to Oslo University Hospital for delayed primary flexor tendon repair in zone 1, 2 or 3. Closed avulsions, sharp cuts and mild crush injuries were included, as long as the condition of the soft tissue allowed direct skin closure and immediate mobilization. The inclusion criteria were age between 18 and 75 years, generally good health and ability to follow the specific rehabilitation protocol. Patients with thumb injuries, replantations, revascularizations, concomitant phalanx fractures or other injuries needing immobilization were excluded. Patients with rupture of the repair were excluded from the analyses at all assessment times.

The original wound was extended in a zigzag fashion and the sheath was opened in the palmar midline with limited pulley release at the site of the repair (Tang, 2007). Direct repair of the flexor digitorum profundus (FDP) tendon was performed with
Yotsumoto-Dona suture (Yotsumoto et al., 2005, Dona et al., 2003). In cases with avulsion or too short distal tendon stump, the tendon was reattached with the TILT method (Tripathi et al., 2009). Totally cut FDS tendons were repaired as well, with Yotsumoto-Dona suture in zone 3 and subzone 2d. In the bifurcation (subzone 2b) and proximal to it where the FDS is flat (subzone 2c), only one slip was repaired in a modified Becker fashion (Paillard et al. 2002). The unrepaired slip was resected (Figure 12). If the FDS tendon was cut near the insertion (subzone 2a), one slip was reattached to the middle phalanx with an intraosseous suture. Partial lacerations with only one slip in continuity were treated with resection of the totally cut slip and preservation the other.

![Figure 12](image)

**Figure 12.** Repair of only one superficialis tendon slip using Becker suture in zone 2b; the other slip is resected.

Associated digital nerve injuries were repaired with standard microsurgical technique; the rehabilitation protocol was not altered. After wound closure standardized dorsal blocking plaster splints were applied with 0-20 degrees of flexion in the wrist and 50-80 degrees in the MCP joints. The splint extended only to the PIP joints, allowing free extension of both PIP and DIP joints. Rubber bands were attached to the nails of the injured fingers and pulleys were placed in the palm.

The patients were randomized to either active extension and passive flexion regime (Kleinert group) or EAM regime (active group). All patients began mobilization on the first day and were instructed by the hand therapists how to perform the exercises. Full passive flexion of the fingers was achieved using the other hand. The Kleinert patients performed 20-30 repetitions every waking hour. Patients in the active group warmed up with 10 active extensions and passive flexions hourly, then released the rubber band and performed 10-20 active un-resisted finger flexions (Figure 13).
Active finger extension and non-resisted active finger flexion exercises in the active group started on the first postoperative day. Note the fresh operation wound without bandage; the wounds were treated with spray dressing.

After 4 weeks the splints and rubber bands were removed in both groups and all continued the same rehabilitation including active flexion exercises thoroughly followed up by the hand therapists. Use of the hand in simple acquired daily living (ADL) activities was allowed after 6 weeks, gradually increasing the load until full gripping force was permitted after 12 weeks.

Twenty-nine patients were randomized to the Kleinert and 24 to the active group. One patient in the Kleinert group and two in the active group were excluded for rupture of the repair. Thirty-two fingers in 28 patients were analysed in the Kleinert group and 37 fingers in 22 patients in the active group. FDP reattachment was carried out in four and
seven fingers and direct suture in 28 and 30 fingers in the Kleinert and the active group, respectively. Fourteen FDS tendons were repaired and four resected in the Kleinert group, 18 repaired and two resected in the active group. The resected FDS tendons were unsuitable for placing of the suture.

The combined AROM of PIP and DIP joints of the active group was insignificantly higher at one, two, three, six and twelve months (Table 2). The AROM of both groups increased significantly to the subsequent assessments. The grip strength did not differ between the groups, and increased significantly in both groups with time. The pinch strength was significantly higher in the active group only at 6 months. The pinch improved significantly at 6 months in both groups, and even at one year in the Kleinert group. The VAS score for ADL use of the injured finger was significantly higher in the active group at

Table 2. Outcome measures. The data is mean (SD). P values for the differences between the groups are enclosed.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Group</th>
<th>1 month</th>
<th>2 months</th>
<th>3 months</th>
<th>6 months</th>
<th>12 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>AROM (degrees)</td>
<td>Kleinert</td>
<td>77 (24)</td>
<td>108 (37)†</td>
<td>119 (36)†</td>
<td>134 (36)†</td>
<td>140 (35)†</td>
</tr>
<tr>
<td>AROM (degrees)</td>
<td>Active</td>
<td>88 (32)</td>
<td>114 (42)†</td>
<td>123 (42)†</td>
<td>137 (32)†</td>
<td>149 (29)†</td>
</tr>
<tr>
<td>p value</td>
<td>Kleinert</td>
<td>0.097</td>
<td>0.555</td>
<td>0.654</td>
<td>0.757</td>
<td>0.261</td>
</tr>
<tr>
<td>Grip (percent)</td>
<td>Kleinert</td>
<td>55 (16)</td>
<td>79 (15)†</td>
<td>90 (11)†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grip (percent)</td>
<td>Active</td>
<td>57 (21)</td>
<td>76 (18)†</td>
<td>90 (15)†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p value</td>
<td>Kleinert</td>
<td>0.651</td>
<td>0.497</td>
<td>0.828</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pinch (percent)</td>
<td>Kleinert</td>
<td>54 (21)</td>
<td>73 (23)†*</td>
<td>88 (25)†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pinch (percent)</td>
<td>Active</td>
<td>62 (17)</td>
<td>86 (20)†*</td>
<td>93 (17)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p value</td>
<td>Kleinert</td>
<td>0.169</td>
<td>0.033</td>
<td>0.348</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VAS ADL</td>
<td>Kleinert</td>
<td>5.9 (2.6)*</td>
<td>7.1 (2.1)†</td>
<td>8.2 (1.7)</td>
<td>8.2 (2.1)</td>
<td></td>
</tr>
<tr>
<td>VAS ADL</td>
<td>Active</td>
<td>7 (1.6)*</td>
<td>7.1 (2.2)</td>
<td>8.4 (1.4)†</td>
<td>9 (1.4)†</td>
<td></td>
</tr>
<tr>
<td>p value</td>
<td>Kleinert</td>
<td>0.042</td>
<td>0.955</td>
<td>0.555</td>
<td>0.073</td>
<td></td>
</tr>
</tbody>
</table>

*Significant difference between the groups (p<0.05).
†Significant improvement compared to previous measurement (p<0.05)
two months, but later we found no significant differences; however, significant improvements were registered at several assessments.

At one month, no finger in the Kleinert group achieved excellent or good functional grade, whereas eight graded good according to the original Strickland criteria (Strickland and Glogovac, 1980) in the active group (p=0.006). We found no significant difference in functional grading later, neither with the Strickland nor Tang (2007) criteria. The final function according to Strickland and Tang was excellent or good in 20/29 (69%) and 21/29 (72%) in the Kleinert, and 28/34 (82%) and 29/34 (85%) in the active group, respectively. These differences were insignificant (p=0.247 and p=0.23 according to Strickland and Tang, respectively).

Totally nine adverse effects were registered in the Kleinert and six in the active group (p=0.257). One FDP tendon in the Kleinert and two in the active group ruptured in week 12 (Kleinert) and week 5 and 6 (active) after repair, in all cases upon sudden and unexpected overload. Reoperation revealed the mechanism of failure: knot loosening in one of the active and cut out in the two others (Kleinert and active). Delayed wound healing or superficial infection was seen in six fingers in the Kleinert group, none was observed in the active group. Transitory swelling and tenderness over the tendon sheath was found in one finger in the Kleinert group and four in the active, all resolving without further surgical intervention. One patient in the Kleinert group developed complex regional pain syndrome. Apart from the immediate re(repairs no further surgical procedures were carried out.

We found better objective and subjective results with early active mobilization compared to Kleinert’s regime in the early phase of rehabilitation, but later the differences became insignificant. We were unable to prove that adding active finger flexion to traditional Kleinert’s regime can improve the long-term results; however, the recovery was faster.
GENERAL DISCUSSION

1) METHODS

Biomechanical investigation of tendon sutures

Paper 1 is an **ex vivo experimental animal study** on deep-frozen porcine tendons. The main advantage of this design is the simplicity. The tendons were extracted from the surrounding tissue for better access, and provided a realistic model for flexor tendon suture in the human zone 2. The specimens were easy to handle, cut, repair and test with a standardized set up.

We chose **porcine tendons** for the study because they were readily available. Porcine flexor tendons are accepted models for human reconstruction and used extensively in tendon studies (Wang et al., 2003, Cao and Tang, 2005, Manchio et al., 2009, Wu et al., 2011). The structure is similar and the diameter is slightly larger than human flexor tendons, close to that of the FDP tendon of the middle finger (Cao and Tang, 2005, Smith et al., 2005). The biomechanical properties of porcine tendons were found comparable to human tendons in an experimental study where repaired tendons of both kinds showed identical ultimate strength. However, the gap resistance after cyclic loading was higher in the porcine tendons, implying superior holding capacity of the suture (Hausmann et al, 2009).

We harvested full-length deep toe flexor tendons from pigs (60-75 kg), after they had been killed at our institution for other ethically approved research not involving their legs. The tendons were **frozen** immediately. When an appropriate number of tendons had been collected, they were thawed at room temperature for 3 hours before the repair and testing. Freezing of the tendons and thawing at room temperature have been widely employed (Hatanake and Manske, 2000, Tang et al., 2001, Kubota et al., 1996), and experimental evidence on repaired human cadaver tendons have demonstrated no influence on the biomechanical measurements (Hirpara et al., 2008).

Cyclic loading and testing of sutured tendons in the tendon sheaths provide a biologically more adequate assessment and can evaluate gliding resistance in addition to
static strength (Amadio et al., 2005). However, linear loading with a straight pull until failure is still the most used method to evaluate the ultimate strength of a repair. Several biomechanical studies have used a set up similar to ours (Wang et al., 2003, Cao and Tang, 2005, Wu et al., 2011). Using cyclic loading, we can simulate the forces acting under finger motion during the rehabilitation. Since modern repair techniques should withstand the forces applied during cyclic testing, which are usually lower than the ultimate force, we would not expect failure after the fulfilled number of cycles. However, gap formation could be evaluated in a functionally adequate way, since the threads of the suture gradually realign after repetitive loading and the repair may increasingly catch in the sheath. On the contrary, the ultimate strength of the repair could only be measured by load to failure, which is usually higher than the forces acting during unresisted finger motion. In the clinical setting, ruptures after flexor tendon repair are usually due to sudden unexpected overload; the linear load to failure model probably imitates this situation better than cyclic loading. The main concern of this model is that we evaluate only the “time zero” strength, i.e. how strong the repair is right after surgery. The posttraumatic and postoperative oedema increases the gliding resistance and decreases the strength during the first days (Amadio et al., 2005). Later, the strength gradually increases simultaneously with the healing process (Yang et al., 2013). In addition, exposed suture material on the surface of the tendon can induce tissue reaction, which could also influence the gliding resistance and the strength of the repair. In vivo animal experiments can probably evaluate the development of the strength of the repair over time better than ex vivo studies, but such studies are more demanding because unloading the operated tendons in animals is difficult.

The ultimate strength is the parameter traditionally applied for comparison of different repairs. The yield force (Figure 14) is more relevant as it may indicate the beginning of failure (Silva et al., 1998). However, gapping has the greatest clinical importance, as it shows the initial response to load with lesser forces. A 2 mm or larger gap that forms under mobilization of the repaired flexor tendon will increase the gliding resistance and catching at the pulleys significantly (Zhao et al., 2004). This may impair the clinical outcome because of rupture or formation of adhesions.

Our novel method for calculating the 2 mm gap is supposed to eliminate the problems with the two traditional methods used previously. Synchronised digitized photo
or video cameras (Yotsumoto et al., 2005, Miller et al., 2007, Tang et al., 2001) can be difficult to use for exact measurements, as the tendons are not solid bodies and the width of the gap may vary around the circumference. Mini displacement transducers are assumed not to affect the mechanism of failure or loading (Tanaka et al., 2004). However, in our study the small attaching wires should have been placed outside the repair with a distance of more than 2 cm to avoid interference with the sutures, increasing the measure error. To avoid these problems, we compared the elongation of the repaired tendons with an imaginary reference tendon obtained by testing intact tendons with the same apparatus. In this model, the gap length is the difference between the elongation of the repaired and the uninjured tendon.

**Suture technique**

It is widely accepted that modern rehabilitation protocols require stronger repairs that withstands the increased load. An in vivo study showed forces up to 35 N acting on the flexor tendons under active unrestricted finger flexion (Schuind et al., 1992). This is the minimum requirement for controlled active rehabilitation regimes. However, most ruptures do not occur during the mobilization sessions, they are often due to some irresponsible act from the patients (Harris et al., 1999). We cannot predict sudden unexpected overload, but we can increase the holding capacity of the repair.

The most accepted way of increasing the strength is the use of **multi-strand repairs**. Many experts advocate the use of minimum four strands while judging two-
strand sutures generally insufficient. Biomechanical studies have proven that increasing the number of sutures crossing the repair site, increases the resistance to gap formation and the failure strength proportionally. Multi-strand repairs have become the standard in many centres, and several case series with these techniques have showed good clinical results (Wu and Tang, 2014). However, their superiority over two-strand repairs has neither been proven in clinical studies nor in systematic reviews (Hardwicke et al., 2014).

There are several other ways to strengthen the repair without increasing the number of strands: the use of stronger suture material, suture diameter of 3-0, proper knotting technique, locking loops, a minimum of 7 mm purchase, proper tensioning of the suture, and stronger peripheral suture (Wu and Tang, 2014). The ideal suture material should have a high tensile strength, be easy to handle, have a good knot holding capacity and induce as little tissue reaction as possible. Monofilament sutures are easy to handle and knot. Braided sutures are generally stronger, but the knot holding is poorer. The problem with resorbable sutures is the loss of strength with time and the tissue reaction. Previous experimental studies have shown superior biomechanical properties of braided polyblend polyethylene (FW) compared to monofilament polypropylene or braided polyester, followed by monofilament nylon and polydioxanone (Lawrence and Davis, 2005, Yamagami et al., 2006).

At least three throws are needed to tie a knot firmly, but more throws are recommended for FW (Wu and Tang, 2014). We tied the sutures with one surgeon’s plus a four-throw square knot in both groups. In a recent study from the Mayo Clinic (Rochester, Minnesota, USA) a new knot configuration, the two-strand-overhand locking knot (Figure 15) was found significantly stronger than a conventional four-throw square knot, and thus recommended for knotting FW (Zhao et al., 2013). We were unaware of this method when performing our studies. The biomechanical properties of this knotting technique are promising. However, clinical studies have not yet proven its efficacy.

Using locking loops instead of grasping loops increased the strength of the two-strand core sutures significantly and decreased gap formation (Hatanaka and Manske, 2000, Tanaka et al., 2004). Placing the locking loops on the side of the tendon instead of on the volar surface led to increased stiffness of the repair (Yotsumoto et al., 2005). Choosing proper suture material for the locking suture is important as well. In
Figure 15. Different knot configurations recommended for tying polyblend polyethylene (FiberWire): (A) One-throw surgeon’s knot with a four-throw square knot (B) two-strand-overhand locking knot

combination with locking sutures, FW provided significantly better biomechanical properties than traditional suture materials, but showed no benefits with grasping sutures (Yamagami et al. 2006, Miller et al., 2007). The recommended diameter of locks in the tendon is a minimum of 2 mm (Wu and Tang, 2014), which is easy to achieve with a side-locking loop suture (Yotsumoto et al., 2005).

The circumferential suture not only smoothen the surface, but is important in resisting initial gap formation (Amadio et al., 2005, Tang et al., 2001). The interlocking horizontal mattress suture has significantly better biomechanical properties than the simple epitendinous running suture or the popular Silfverskiöld cross-stich, and it is relatively easy to perform although more time consuming (Dona et al., 2003). The increased number of exposed suture strands on the surface may worsen gliding resistance (Tanaka et al., 2004). However, the similar cross-stitch circumferential suture did not increase the gliding resistance significantly in human cadaver tendons (Kubota et al., 1996).

Combining the above-mentioned tactics, it is possible to increase the strength of the repair without increasing the number of strands. Biomechanical studies have approved that modern two-strand repairs could have high tensile strength and stiffness (Komatsu et al., 2007; Yotsumoto et al., 2005). They can be equally strong as a four-strand cruciate repair (Brockardt et al., 2009) and have higher ultimate strength than an eight-strand repair (Kuwata et al., 2007).
The authors mentioning two-strand sutures in comparative studies and review articles are usually referring to modified Kessler type repairs, which are considered to be insufficient for aggressive rehabilitation. However, combined with a dynamic splint, the Kessler suture could provide reliable results, assuming thorough follow up by the therapist. Despite the great enthusiasm for modern techniques, one of the best results ever (98% excellent and good) was published from a military hospital using modified Kessler repair (Chow et al., 1987). In addition, modified Kessler repair was used in the first series reporting EAM (Cullen et al., 1989, Small et al., 1989) and in a recent study comparing CPM with PAH as well (Farzad et al., 2014). In a short clinical series excellent results were obtained with a heavy gauge locking two-strand suture combined with aggressive EAM (Hatanaka et al., 2002). In the Mayo Clinic (Rochester, MN, USA), one of the most acknowledged trendsetter hand surgery centres in the world, the Pennington type two-strand suture technique is used routinely (Pennington, 1979, Tang et al., 2013).

We chose side-locking loop technique (Yotsumoto et al., 2005) with the transverse component placed 10 mm from the cut ends, performed with 3-0 FW, tied with one surgeon’s plus four-throw square knot, and completed with interlocking horizontal mattress suture (Dona et al., 2003). This combined repair technique (Yotsumoto-Dona suture) is supposed to fulfil most of the requirements for an appropriate flexor tendon suture (Wu and Tang, 2014), despite being a two-strand method.

**Retrospective studies**

Since our results with the old routine methods for flexor tendon repair were not always optimal, we looked for alternatives. Our biomechanical study proved the strength of the Yotsumoto core suture, and we began to use it for both tendon repair and reattachment combined with TILT. Because of the usual complications with POS that was the previous routine for tendon reattachment in our department, we began to use TILT, which was supposed to prevent soft tissue irritation.

**Paper 2** is a case-control observational study. The case-control design is mostly used in epidemiological studies, for investigation of rare diseases or exposures. However, it can be used in interventional studies as well for comparison of different procedures. As we had subjectively good experience with TILT, we intended to document it through a
retrospective analysis of the two methods for tendon reattachment. Only a limited number of surgeons carried out TILT, while others continued to use POS. The POS group is not a true historical control used only before a certain date. The method used was the surgeon’s choice. The lack of randomization is the major disadvantage of this design. Selection bias is possible and the results could be confounded. Therefore case-control studies are placed low in the hierarchy of evidence. However, this is the most frequent type of clinical studies, easy to perform, inexpensive, short in duration and applicable to small groups. Our study was originally meant as a preliminary study, but after the initial results we did not find it necessary to continue with a more complex clinical trial.

Paper 3 is a retrospective cohort study, which is originally an epidemiological study design. In retrospective cohort studies the development of particular diseases or conditions is the usual outcome. The study aims to determine the influence of various exposures on this development, often comparing with individuals without the same exposure. In these studies the investigator collects data from previous records and does not follow up the participants over a long time. All events that we investigate have occurred in the past, and all records have already been conducted before performing the study.

The advantages over prospective cohorts are the simplicity and the need for less time and less expense, since the resources are exclusively aimed at collecting data from the clinical records. It is possible to investigate multiple outcomes, and if the outcome is rare, the individuals are already identified when collecting the data. The effect of multiple exposures on the cohort can be evaluated as well. Different patient, injury and surgery related parameters were defined as “exposures”, or predictors as we called them.

The major disadvantage of the retrospective cohort is the possibility of selection bias and misclassification. The clinical records could be insufficient and the investigator must rely on others’ recordkeeping accuracy. Missing data is one consequence of this. Information that is not recorded cannot be collected. Therefore, we had to abandon suture material as a possible predictor due to the large proportion of missing data in the medical documentation. Large sizes of retrospective cohorts can compensate this problem.

Another issue regarding our study is the length of follow up. Some patients had been released already after 8 weeks, if the progression was satisfactory and no adverse
effect needing action was detected. Since the participants were chosen from clinical everyday work, we had to accept this situation in order to gain a large study population.

Some explanatory variables, mostly patient and injury specific ones, are known from previous papers as accepted risk factors for suboptimal functional results after flexor tendon surgery. The variables used in our study were chosen based on the recommendations in the literature and from clinical judgment; we included some surgery related variables as well. The treatment of the tendon sheath and pulley is relevant only in the zones 1 and 2. The variables associated with the FDS tendons are relevant only in the zones 2 and 3 injuries. As the effect of these variables could not be evaluated in all zones, we carried out subgroup analyses, but these subgroups were defined a priori. Without the subgroups, we should exclude the zones 1 and 3 from the assessment, keeping only zone 2, where both FDS and sheath related variables are relevant. In that case the sample size would be lower, which could weaken our statistical analysis.

Treatment of flexor tendon injuries requires teamwork, and active participation of the patient is mandatory. Cooperation is difficult to define and measure, so we could not include this important variable in our analyses.

**Prospective clinical trial**

**Paper 4** is a **prospective randomized controlled trial** (RCT). This study design is the gold standard in clinical research and considered to be the most reliable form of clinical experiment in the hierarchy of scientific evidence. The participants are randomly allocated to either the group receiving the intervention under investigation or to a group receiving the standard treatment as control. The randomization minimizes selection bias, and the comparison of the outcome in the groups allows the researchers to determine the effect of the treatment. Our study was a superiority trial where we wanted to investigate whether EAM gives better results than Kleinert’s regime or not.

The most reliable type of RCTs is double blinded, where neither the participants nor the outcome assessors know which treatment was received. However, if an RCT involves a treatment, in which active participation of the patient is necessary (e.g., physiotherapy), the participants cannot be blinded to the intervention. In addition, our evaluating therapists were also involved in the rehabilitation of the patients. We consider
knowledge of the group allocation quite unlikely to affect objective measurements like AROM or grip strength. It was practically difficult to prevent patients in the Kleinert group flexing their fingers actively, since information of both treatment regimes was necessary for providing informed consent. The Kleinert patients knew that they could have been randomized to the active group as well. We tried to prevent patients from different groups to meet postoperatively or during the sessions at the hand therapy department.

RCTs are usually associated with higher costs and longer duration. No extra expenses were triggered by our study because the participants should undergo surgery followed by rehabilitation anyway. Conflict of interest is an issue regarding testing of new implants or drugs. Neither surgeons nor therapists were involved in any conflict of interest associated with our trial because no additional material, device or drug was needed to carry out the study.

**Applied surgical techniques**

The methods used for flexor tendon repair in our RCT were chosen based on results from previous studies, recommendations from the literature and clinical experience. Yotsumoto-Dona suture was chosen for direct flexor tendon repair after our biomechanical study, and TILT for reattachment of the FDP tendon after good clinical experience with this method, using the same core suture configuration.

There is no consensus in the literature about treatment of concomitantly injured FDS tendons. Three comparative studies have shown significantly better outcomes with simultaneous repair of both the FDP and FDS tendons (Lister et al., 1977, Nielsen and Jensen, 1984, Moriya et al., 2015), whereas others have not (Brunelli et al., 1983, Ikuta and Tsuge, 1985, Tang, 1994). Earlier the concomitantly cut FDS tendons were routinely resected in our department, but recently we have recommended repair. We consider repair of the FDS tendon important in promoting independent flexion of the fingers and a more natural pattern of motion. In addition, sparing the vinculum system could support the intrinsic healing mechanism.

The FDS tendon can be repaired with the same technique proximally where the anatomy is similar to the FDP tendon. However, in subzone 2c and distally where the tendon flattens and forms the bifurcation and the Champer’s chiasma, a more delicate
repair technique is necessary. Suture of both slips in the bifurcation increases the bulkiness of the repair. One strategy for reducing the gliding resistance in subzone 2c is widening of the A2 pulley with a pulley-plasty, which works well in cadaver studies (Paillard et al., 2002), but substantially increases the risk of adhesions in vivo (Tang et al. 2007). Another possibility is resection of one FDS slip and repair of the other, which have proved equally efficient in biomechanical studies (Paillard et al., 2002, Zhao et al., 2002). In a cadaver study repair of only one FDS slip with Becker suture was found significantly stronger (28.8 N, SD 9.0) than modified Kessler (16.4 N SD 4.5) or running zig-zag (15.0 N, SD 5.7) suture (Paillard et al., 2002). We acquired the latter strategy: repair of one slip with Becker suture and resection of the other. However, the FDS tendon was not suitable for placing the suture in 6 fingers and resection was performed.

Closure of the tendon sheath and preservation of the A2 and A4 pulleys were advocated previously. However, in experimental or clinical studies closure of the synovial sheath has not improved the outcomes compared to leaving the sheath open. In the last decade, limited release or “venting” of the main pulleys has been recommended to decompress oedematous flexor tendons and decrease gliding resistance (Amadio et al., 2005, Elliot and Giesen, 2013, Tang, 2007; Tang et al., 2014). Incision of a part of the A2 or the entire A4 pulley has not been found to cause bowstringing or inferior functional results, and is permissible when other pulleys and most of the sheath are intact. The length of the opening is recommended not to exceed 1.5-2 cm; however, the exact maximum length has not been determined. Recent clinical studies have proved the safety of releasing the entire length of the A4 and even the entire A2 pulley, eventually combined with releasing the adjacent cruciate pulleys (Moriya et al, 2016a and 2016b). Excellent or good functional grading was achieved without clinically significant bowstringing in 20/22 and 6/7 fingers, with total release of the entire A4 and A2 pulleys, respectively. We acquired the strategy of partial pulley release. However, we did not open more than the recommended 1.5-2 cm, with partial A2 or entire A4 release if necessary.
EAM combined with Kleinert’s regime

Since publications on EAM have shown promising results and such protocols have become popular in recent years (Pettengill, 2005, Tang et al., 2013), we wanted to evaluate the efficacy of EAM in a clinical study compared with the previous routine method, the Kleinert’s regime. According to some authors, several therapists and patients find it easier to perform EAM than traditional Kleinert-type rubber band mobilization (Amadio et al., 2005, Elliot and Giesen, 2013). The EAM regime that we used could be criticized for not being a true early active regime because of the use of rubber bands. The rubber bands may have counteracted a true active motion of the repaired digits, but the patients can definitively perform active finger flexion by releasing the traction. Several other units no longer use rubber band traction. However, a similar regime, EAM combined with Kleinert’s traction, has also been applied in other publications where the patients were allowed unresisted active finger flexion, whereas rubber bands kept the fingers bent between the active movements (Kitsis et al., 1998, Moriya et al., 2015). Because our study was interventional, we did not want more than one difference between the groups, namely allowing active flexion or not. Therefore, we chose the same dynamic splint with rubber bands for all patients, even the active group.

Our dynamic splint was standardized with 0-20 degrees of flexion in the wrist and 50-80 degrees in the MCP joints. The splint extended only to the PIP joints, allowing free extension of both the PIP and DIP joints, as recommended by May et al. (1992). Rubber bands were attached only to the injured fingers as in the original Kleinert’s regime (1967). Safety pins were used as pulleys in the palm for increased flexion effect on the fingers (Pettengill, 2005). We used old-fashioned plaster instead of modern thermoplastic splints to decrease the temptation of the patients for occasional removal.

Functional evaluation of the outcome

The categorical description of finger function is usually based on the overall PIP and DIP AROM. The original Strickland grading system is most commonly used in the literature (Strickland and Glogovac, 1980). According to these criteria, a minimum of 70% of the normal PIP+DIP AROM is needed to achieve the grade “good”. The AROM of the
fingers was compared with a 175 degrees standard mean value, making the evaluation easier. Other grading systems such as Buck-Gramcko, TAM or modified Strickland, have been used in some publications (Small et al., 1989, Gerard et al., 1998, Riaz et al., 1999, Hung et al., 2005, Frueh et al., 2014). As these systems include also the MCP AROM or demand less AROM for excellent or good gradings, comparison of the results is difficult.

The Tang system (2007) is similar; however, the AROM is compared with the corresponding finger of the contralateral hand. The excellent and good grades are further divided into plus and minus subgrades by the grip strength and “quality of motion”, based on the investigator’s subjective judgment of the coordination, visual arc and speed of motion. Tang’s system includes the grade “failure”, when the AROM is less than 30% of the contralateral finger, but the tendon has not necessarily ruptured. We also acquired this system because it included the grip strength; however, it does not change the basic grading, just adding plus or minus.
2) STATISTICS

In our studies descriptive statistical methods were used to analyze data collected from specific samples. SPSS computer software was employed for execution of the analyses. The level of significance, the probability of rejecting the null hypothesis when it is true, was set to 5% in all studies.

In Paper 1 continuous outcome variables were compared with Mann-Whitney U test. A non-parametric test was chosen because of the small sample size, 9 specimens in each group. We used all tendons that were available. Power calculation was not carried out. However, the group sizes in similar studies were usually between 9 and 11 (Wang et al., 2003, Cao and Tang, 2005, Yotsumoto et al., 2005, Komatsu et al., 2007, Manchio et al., 2009, Corradi et al., 2010, Wu et al., 2011). The Student T-test was usually employed in these studies despite the small sample sizes. It is difficult to prove normal distribution of such small samples, why we chose a non-parametric test. In previous studies continuous outcome variables were described by mean and SD. Based on non-parametric analyses we used median and interquartile range. The disadvantage of this strategy was difficulties in directly comparing our results with others’. However, in our opinion a non-parametric test is methodically more robust.

The number of specimens experiencing yield in the two groups were analyzed using cross tabulation. As the numbers in this comparison of two proportions were very low, the Fisher’s exact test was considered to be more correct than the often-used chi-squared test.

Since the two groups in Paper 2 were not randomly assigned, we compared the baseline characteristics statistically in addition to the defined outcomes. The continuous variables with approximately normal distribution (age and ROM) were analysed with independent-sample T test. The delay of surgery was analyzed using Mann-Whitney U test as the distribution of data was skewed. The differences in binomial variables (sex, smoking, side, dominance, number of multiple finger injuries, number of fingers with excellent or good function, complications and reoperations) were compared using the Fisher’s exact test. This test provides a more robust calculation than the chi-squared test when the numbers are low. In our analyses these numbers were often under 10. The comparison of multinomial variables (the finger injured, degree of soft tissue damage and
associated injuries) needed larger contingency tables than $2 \times 2$. In these calculations we used the chi-squared test.

Because significant differences in any baseline characteristics could be expected, we carried out multiple logistic regression to compensate for these variations. The dependent variable was achieving excellent or good functional grading or not, both at 8 weeks and at the last documented evaluation. The regression models were adjusted for age and gender, since it is the usual procedure in medical research. We employed the odds ratio (OR) and 95% confidence interval (95% CI) for excellent or good functional grades from these regression models as the measure of the effect size, describing the strength of the association between the reattachment method and the grading of outcome.

We used regression analysis in Paper 3 to study the association between chosen exposure/explanatory variables and the outcome. In this complicated study, methodical advice was gained from a statistician.

We chose a continuous dependent variable and performed multiple linear regression. The data was analyzed by finger, as the whole dataset, and in two subgroups, according to the injury localization and the relevance of some explanatory variables as mentioned before. The outcome variable was AROM, both at 8 weeks and at the last follow up. The sample size at the 8 weeks’ analysis, included all zones, was 332. As only 225 had a minimum of 3 months follow up, the sample size was smaller in the second series. Multiple linear regression analyses were carried out in six series. We included both continuous and categorical explanatory variables. In preliminary simple regression analyses, we tested the effect of multinomial categorical variables. When it was possible we merged them into binary “dummy variables”, as required by the regression models. The aim of it was to distinguish between the categories with significant and insignificant effects, e.g. injury between subzones 1C and 2C or an associated fracture. The treatment of the FDS tendon was merged into new variables, “condition of FDS”, with three categories: FDS tendon in continuity; repaired; or not repaired. Interactions between the variables were checked and comorbidity was excluded as an explanatory variable because of the strong collinearity with smoking, which had a larger effect on the results. The suture material was excluded as well because of the high proportion of missing data and
the excessive collinearity with repair technique. Missing data was not replaced, no imputation method was used; these fingers were simply abandoned from the analyses.

The models were accomplished with backward analysis; the Akaike Information Criterion (AIC) was used to select the best models. In order to gain the best model fit, minimize the number of residuals and the information lost, some variables with insignificant effects (p>=0.05) were kept in the models.

Multiple linear regression analyses aimed to predict the AROM using the explanatory variables. The adjusted R squared values of the regression models indicate the proportion of variances in observations that the models could explain. The intercept represents the optimal predicted AROM, which is changed by the sum of effects from the different predictors in each case; the 95% CI represents the uncertainty of the estimations. The regression coefficient is the mean value of the changes in AROM when the value of the particular explanatory variable changes with one unit; in case of a linear variable such as age or delay to surgery the coefficient should be multiplied by the value of the variable.

Since Paper 4 is a clinical experiment, the sample size was calculated, with 80% power and 5% level of significance. The clinically significant difference was defined as 30 degrees and the SD was estimated to be 40, based on previous studies. Considering 20% dropouts, we decided a minimum group size of 34. Since we evaluated fingers and not patients, the inclusion was closed when both groups reached this level. The results for each finger were evaluated independently.

The continuous variables (AROM, grip and pinch strength, and VAS score) showed approximately normal distribution. The sample sizes were also sufficient, so we applied parametric tests for the statistical analyses, since these were most frequently used in similar studies. The group variables were compared using independent samples T-test. The changes between subsequent times of assessment were compared with paired T-test. The proportion of fingers with excellent or good function was analysed with Fisher’s exact test. As mentioned above, this test provides a more robust calculation than the chi-squared test, because in our analyses the numbers were often fewer than 10.
3) RESULTS

Strength of Yotsumoto-Dona suture

We found the Yotsumoto-Dona suture to be stronger than the classical modified Kessler suture, and strong enough to allow EAM after repair. More Kessler than Yotsumoto-Dona sutures underwent yielding (6/9 vs 2/9). All Yotsumoto-Dona specimens performed a yield force exceeding 35 N compared to just four in the Kessler group. The explanation could have been a change of the suture configuration under load. The threads of the Kessler sutures could have started to slide along the longitudinally arranged fibres at forces under 35 N, whereas in the Yotsumoto-Dona sutures this occurred only at higher forces. Finally, all core sutures failed when the knot broke except for the three Yotsumoto-Dona sutures where the knots had loosened. Two of them were also those who underwent yield. Probably, we could have avoided knot loosening and increased the tensile strength of the Yotsumoto-Dona sutures by using other knotting technique. The knot we used (one-throw surgeon’s and four-throw square knot) was not tested in the study of Zhao et al. (2013), but one surgeons’ plus three-throw square knot was found significantly weaker than two-strand-overhand locking knot. We were unaware of this method when performing our studies.

The epitendinous sutures behaved also different under load. All the simple running sutures failed by pulling-out. The interlocking horizontal mattress sutures underwent multiple ruptures at the intersections before the threads pulled out, implying that this configuration is more resistant to suture pull-out and probably contributes more to gap resistance.

The biomechanical properties of the Yotsumoto-Dona suture in our study are comparable with recent multi-strand sutures combined with simple running suture (Table 3) (Wu and Tang, 2014). The 2 mm gap forces are very similar, and the ultimate strength of the Yotsumoto-Dona suture is even higher than the other mentioned repairs. No clinical studies have compared the outcomes of modern two-strand and multi-strand repairs with the use of the same rehabilitation protocol.
Table 3. Biomechanical comparison of Yotsumoto-Dona suture with multi-strand repairs.

<table>
<thead>
<tr>
<th>Repair methods</th>
<th>Tendon</th>
<th>Number of strands</th>
<th>Suture</th>
<th>2 mm gap force (SD)</th>
<th>Ultimate strength (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-Tang + running (Wang et al., 2003)</td>
<td>Porcine</td>
<td>6</td>
<td>4-0 Supramid</td>
<td>46.2 (5.2)</td>
<td>61.9 (6.0)</td>
</tr>
<tr>
<td>U-Tang + running (Cao and Tang., 2005)</td>
<td>Porcine</td>
<td>6</td>
<td>4-0 Supramid</td>
<td>36.8 (4.0)</td>
<td>43.4 (4.3)</td>
</tr>
<tr>
<td>Lahey - only core (Manchio et al., 2009)</td>
<td>Porcine</td>
<td>4</td>
<td>3–0 Prolene</td>
<td>—</td>
<td>63.8 (7.5)</td>
</tr>
<tr>
<td>Staggered + running (Corradi et al., 2010)</td>
<td>Cadaver FHL</td>
<td>4</td>
<td>3-0 Ethilon</td>
<td>41.3 (4.3)</td>
<td>88.6 (6.7)</td>
</tr>
<tr>
<td>Cross-lock + running (Wu et al., 2011)</td>
<td>Porcine</td>
<td>4</td>
<td>4-0 Supramid</td>
<td>31.9 (6.1)</td>
<td>40.2 (3.9)</td>
</tr>
<tr>
<td>Yotsumoto-Dona (Paper 1)</td>
<td>Porcine</td>
<td>2</td>
<td>3-0 FiberWire</td>
<td>32.8 (8.4)*</td>
<td>94.7 (21.2)*</td>
</tr>
</tbody>
</table>

*The results of Paper 1 were published as median and interquartile range, but we also calculated the mean and SD from the same database, for the comparison in this table.

**FDP reattachment**

We found a higher proportion of excellent or good functional results with the TILT method compared to pull-out suture; however, the difference was significant only at 8 weeks. Our results with TILT are comparable with another study on 20 tendon reinsertions, either through the bone and nail complex with an external button, or through a transverse tunnel in the tuberosity of the distal phalanx (Moiemen and Elliot, 2000). They found excellent or good results with the original Strickland criteria (Strickland and Glogovac, 1980) in 14/20 fingers (70%). This is slightly better than our results with totally 30/48 (63%) excellent or good rating. With TILT alone we achieved excellent or good results in 10/13 (77%), but the numbers are too low to conclude.

The usual complications with the POS are infection and irritation of skin, nerve, germinative matrix and nail. The complication rate varies from 35 to 65% in previous publications (Gerbino et al., 1991, Kang et al., 2008); hence the 12/35 (38 %) observed in
our material is comparable with the literature. We did not observe any complication with TILT, implying it is a safer alternative than POS.

**Patient and injury related predictors**

In Paper 3 the observed mean (SD) AROM was 98 (40) and 114 (45) degrees. Excellent or good function was achieved in 95/332 (29%) and 107/225 (48%), at 8 weeks and at the last follow up, respectively. This rate is inferior to the 80% that is the expected late result in the literature (Elliot, 2002, Tang, 2013). However, the study population is very inhomogeneous with various combinations of the defined explanatory variables. This dataset with such a great variation of observations is ideal for identifying the predictors of the dependent variable.

From previous papers age, smoking, soft tissue damage, zone 2 injury, multiple finger injuries, delay of surgery, associated FDS and nerve injuries and immobilization are known risk factors for suboptimal functional results after flexor tendon surgery (Table 4) (McFarlane et al., 1968, Silfverskiöld et al., 1993, Kasashima et al., 2002, Elhassan et al., 2006, Trumble et al., 2010). We investigated a considerably larger number of fingers (patients) and included crush injuries in the analyses as well. Moderate crush injuries and concomitant stable phalangeal or metacarpal fractures do not contraindicate flexor tendon repair as long as early mobilization is possible; however, less favourable results can be expected in these cases (Tang, 2007, Starnes et al., 2012). Accompanying phalangeal fractures and smoking have been linked to poor functional results of tendon surgery (Slattery, 1988, Trumble et al, 2010). Both findings were confirmed by our study. Digits where nerve repair was performed have shown significantly reduced AROM compared with isolated flexor tendon repairs (Elhassan et al., 2006). Painful nerve injuries can interfere with mobilization and theoretically protect against rupture (Dy et al., 2012b). However, we were unable to identify any correlation between concomitant nerve injury and the functional results.

It is widely accepted that zone 2 injuries have poorer functional outcome than injuries in other zones (Hung et al., 2005). Subzone 2c, which is the narrowest part of the sheath, is considered the most problematic. Our subgroup analyses revealed most
Table 4. Comparison of publications on risk factors for suboptimal functional outcome.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Fingers (patients)</th>
<th>Study population</th>
<th>Identified risk factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>McFarlane et al. (1968)</td>
<td>100 (88)</td>
<td>36 sutures, 64 grafts; immobilization</td>
<td>Age, soft tissue conditions, associated FDS injury</td>
</tr>
<tr>
<td>Silfverskiöld et al. (1993)</td>
<td>154 (135)</td>
<td>Sharp cuts; Dynamic splint treatment</td>
<td>Multiple finger injuries, delayed treatment, AROM at 3 weeks</td>
</tr>
<tr>
<td>Kasashima et al. (2002)</td>
<td>29 (29)</td>
<td>FPL injuries; clean cuts; immobilization or dynamic splinting</td>
<td>Zone of injury, postoperative immobilization, retraction of proximal tendon stump</td>
</tr>
<tr>
<td>Elhassan et al. (2006)</td>
<td>41 (35)</td>
<td>2-14 years of age; immobilization or dynamic splinting</td>
<td>Associated nerve injury</td>
</tr>
<tr>
<td>Paper 3</td>
<td>356 (291)</td>
<td>&gt;7 years of age; sharp cuts and crush injuries</td>
<td>Smoking, skeletal injury, subzones 1c-2c, little finger injury, operation technical details, type of rehabilitation,</td>
</tr>
</tbody>
</table>

Functional problems in injuries localized between the A4 and A2 pulleys (subzones 1c to 2c). Possible explanations may be simultaneous injury to the FDS chiasma, digital nerves or PIP joint capsule. These correlations were not proven by our data. The main (A) pulleys could increase the resistance to gliding, especially if release was not performed, by catching the tendons, leading to adhesions or ruptures.

The results of flexor tendon repair in the little finger have been suggested to be inferior to other fingers in previous publications (Gault, 1987, Elliot, 2002, Moriya et al., 2015). Orkar et al. (2012) compared zone 1 or 2 flexor tendon repairs in 60 index and 108 little fingers. Their findings favoured the index finger for both AROM and functional gradings at 5, 8 and 12 weeks; however, the differences were insignificant. They found significantly greater PIP contracture in zone 1 injuries of the little fingers. Our results confirm that injury to the little finger in zone 1 and 2 is a negative predictor for AROM.
Treatment related predictors

The effect of operative technical details has not been analysed in previous studies dealing with predictors of results of flexor tendon repair. The use of stronger suture materials, stronger repair techniques and limited pulley release are widely recommended in the literature, based on experimental evidence and clinical investigations (Amadio et al., 2005, Elliot and Giesen, 2013, Tang, 2007; Tang et al., 2014). We confirmed the role of these factors in the clinical setting. Delay of surgery was also found to be a statistically significant predictor; however, its effect was small (4 degrees reduction in AROM after 14 days of delay) and could be outweighed by other factors such as age, smoking or surgery related details, which had higher regression coefficients and therefore larger effect on the predicted AROM. The prognosis of a delayed repair depends on the localization of the injury. If the vincula are intact and retain the tendon within the sheath, the chance for good results will not decrease as fast as with retracted tendons. Unretracted tendons can be repaired directly after delays of more than a month (Tang, 2007). McFarlane et al. (1968) reported successful direct repair after several months provided it could be done without undue tension.

Our study indicates better functional results with Yotsumoto-Dona compared to traditional Kessler suture. This modern two-strand repair increases the final expected AROM with 36 degrees; the difference is enough to improve a minimum of one category in the functional assessment scale. With respect to the 8 weeks AROM, the Yotsumoto-Dona suture was found to be superior also to a four-strand double Kessler suture, but no difference was found in the late results. However, the number of the double Kessler sutures was very small.

In our material concomitantly cut and repaired FDS tendon decreased the expected early and late AROM with 9 and 8 degrees, respectively. In addition, the resection or untreated complete division of the FDS tendon decreased the AROM with further 9 and 8 degrees, respectively, implying that FDS repair is a significant positive predictor of the functional results. Lister et al. (1977) found more frequently excellent or good function after FDS repair (18/21, 86%) compared to FDS resection (3/7, 43%) in conjunction with Kleinert’s rehabilitation after primary FDP repair. Similarly, Nielsen and Jensen (1984) found significantly more excellent or good function after FDS repair (26/35, 86%) compared to FDS resection (5/7, 71%).
74%) than after resection (13/32, 41%). In a recent cohort study of patients with EAM (Moriya et al., 2015) significantly better AROM was found in 50 fingers with concomitant FDS repair (mean 231, range 169-286 degrees) compared to 12 fingers with FDS excision (205, 143-275 degrees). However, the results were not significantly different from the 10 fingers with untreated FDS (242, 204-272 degrees). In our preliminary analysis, no difference was found between FDS resection and untreated FDS cut. Therefore, these categories were merged into the common category “FDS not repaired”.

We found closure of the tendon sheath and suture or preservation of the main pulleys to be significant negative predictors of the early functional results, implying 15 degrees of reduction of the predicted 8 weeks’ AROM. Suture of the sheath or pulley was not performed routinely; however, the surgeon could consider it depending on the extent of the injury and the conditions of the soft tissue. If the surgeon tried to preserve the A2 or A4 pulleys, the oedematous tendon could catch at the edge of the pulleys. When the injury was underneath the A4 pulley, it was sometimes repaired, either with direct suture or with pulley-plasty. In crush injuries, the pulleys were often found seriously damaged. If so, pulley reconstruction with sheath flaps was considered. In these cases, the prognosis was worse because of the conditions of the soft tissue. The role of the pulley reconstruction itself in suboptimal results is unclear. However, we found significantly better AROM in fingers with simple opening of the synovial sheath and release of the affected pulleys, which complies with the recommendations in the literature. EAM rehabilitation was also a predictor, though insignificant, for the 8 weeks AROM in pooled zone 1 and 2 injuries, see below.

Recently attention has been drawn to the surgeon’s experience, which has been accepted as an important factor influencing the outcome of tendon surgery (Tang, 2009 and 2013). In our department, the less experienced surgeons carried out the operations with the assistance of more experienced surgeons until judged sufficiently skilled. Hence, the highest level of experience in the operating team often exceeded the experience of the operating surgeon. We were unable to prove the operating surgeon’s experience to be a significant predictor of the outcome.

One reason that we used the functional evaluation at 8 weeks was the larger sample size, which improved the statistical models. The other reason is that the long-term outcome is significantly correlated to the early results. Silfverskiöld et al. (1993) found the
ROM at 3 weeks to be a significant predictor of the final function. We found a significant correlation between the AROM at 8 weeks and at the final review. Several predictors of the 8 weeks AROM (pulley release, FDS treatment and rehabilitation) were no longer significant at later analyses, probably due to the improvement in finger function or the smaller sample size.

Looking at the results in Paper 3, we were unable to influence the patient and injury related factors; however, we could recommend several actions: patients to stop smoking and surgeons to use stronger suture techniques, repair concomitant FDS tendon injuries, perform limited pulley release if necessary, and mobilize the fingers after FDP repair with EAM rehabilitation.

**EAM rehabilitation**

Generally, excellent or good function has been reported in 70-80% of the digits after primary flexor tendon repair (Baktir et al., 1996, Cullen et al., 1989, Elliot et al., 1994, Elliot, 2002, Moriya et al., 2015, Tang, 2005 and 2013). Clinical evidence exists for the superiority of early mobilization of repaired tendons compared to immobilization. Publications on EAM showed promising results and such protocols have become popular in recent years (Pettengill, 2005, Tang et al., 2013).

The subgroup analysis of pooled zone 1 and 2 repairs in Paper 3 showed EAM as a positive predictor of AROM at 8 weeks, increasing the expected AROM with 20 degrees compared to Kleinert’s regime. However, our other regression models showed no superiority of EAM combined with rubber band traction, as we used it.

In Paper 4 we were unable to demonstrate that a postoperative regime allowing patients to flex their fingers actively improved the late results, but the functional recovery was faster. No significant difference in AROM was found between the Kleinert and active groups twelve months after repair. Almost all measurements at every evaluation favoured the active group, but only a few of the secondary outcomes were significantly better compared with the Kleinert group. Both Paper 3 and 4 suggest faster functional recovery after EAM, but the long-term results were similar to the Kleinert’s regime. Frueh et al. (2014) found comparable results in a non-randomized study: significantly better AROM with EAM at 4 weeks compared to the Kleinert’s regime; however, the difference
Table 5. Comparison of clinical results with different EAM regimes after FDP repair.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Repair method</th>
<th>Number of strands</th>
<th>Follow-up (months)</th>
<th>Excellent or good function</th>
<th>Rupture rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>True Early Active Motion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baktir et al., 1996*</td>
<td>Modified Kessler</td>
<td>2</td>
<td>12</td>
<td>40/47 (85%)</td>
<td>2/47 (4%)</td>
</tr>
<tr>
<td>Sebesy and Szloboda, 1998</td>
<td>Lee</td>
<td>4</td>
<td>6</td>
<td>33/40 (83%)</td>
<td>2/40 (5%)</td>
</tr>
<tr>
<td>Braga-Silva and Kuyven, 2005</td>
<td>Modified Kessler</td>
<td>2</td>
<td>12</td>
<td>53/54 (98%)</td>
<td>4/54 (7%)</td>
</tr>
<tr>
<td>Navali and Rouhani, 2008</td>
<td>Strickland</td>
<td>4</td>
<td>3</td>
<td>15/16 (94%)</td>
<td>0</td>
</tr>
<tr>
<td>Al-Qattan and Turaiki, 2009</td>
<td>Figure of eight</td>
<td>6</td>
<td>4</td>
<td>49/50 (98%)</td>
<td>1/50 (2%)</td>
</tr>
<tr>
<td>Al-Qattan, 2011</td>
<td>Figure of eight</td>
<td>6</td>
<td>6</td>
<td>36/36 (100%)</td>
<td>0</td>
</tr>
<tr>
<td>Sandow and McMahon, 2011</td>
<td>Adelaide (cruciate)</td>
<td>4</td>
<td>3</td>
<td>44/65 (68%)</td>
<td>3/65 (5%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>270/308 (88%)</td>
<td>12/308 (4%)</td>
</tr>
<tr>
<td><strong>Early Active Motion + Kleinert’s</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kitsis et al., 1998</td>
<td>Modified Kessler + Halstedt</td>
<td>2**</td>
<td>6</td>
<td>192/208 (92%)</td>
<td>6/208 (3%)</td>
</tr>
<tr>
<td>Moriya et al., 2015</td>
<td>Yoshizu</td>
<td>6</td>
<td>24</td>
<td>93/112 (83%)</td>
<td>6/112 (5%)</td>
</tr>
<tr>
<td>Paper 4, active group*</td>
<td>Yotsumoto + Dona</td>
<td>2**</td>
<td>12</td>
<td>28/36 (82%)</td>
<td>2/39 (5%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>313/356 (88%)</td>
<td>14/359 (4%)</td>
</tr>
<tr>
<td><strong>Place And Hold (+ Kleinert’s)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klein et al., 2003</td>
<td>Double Kessler or Strickland</td>
<td>4</td>
<td>3</td>
<td>35/40 (88%)</td>
<td>1/40 (3%)</td>
</tr>
<tr>
<td>Osada et al., 2006</td>
<td>Triple-looped</td>
<td>6</td>
<td>13</td>
<td>26/27 (96%)</td>
<td>0</td>
</tr>
<tr>
<td>Hoffmann et al., 2008*</td>
<td>Lim-Tsai</td>
<td>6</td>
<td>3</td>
<td>39/50 (78%)</td>
<td>1/50 (2%)</td>
</tr>
<tr>
<td>Trumble et al., 2010*</td>
<td>Strickland</td>
<td>4</td>
<td>12</td>
<td>51/54 (94%)</td>
<td>2/54 (4%)</td>
</tr>
<tr>
<td>Farzad et al., 2014*</td>
<td>Modified Kessler</td>
<td>2</td>
<td>2</td>
<td>24/31 (77%)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>175/202 (87%)</td>
<td>4/202 (2%)</td>
</tr>
</tbody>
</table>

* Comparative studies; the groups with best result are included from these papers.

** Two-strand suture combined with complex epiteninous suture
was no longer significant at 12 weeks. The muscles are probably better maintained under activation with less atrophy and improved strength at removal of the splint compared to passive mobilization. This may be the mechanism underlying enhanced pinch strength of the actively mobilized fingers as well. The grip strength did not differ, indicating the strength of the whole hand was not influenced by the rehabilitation regime.

We reviewed publications on EAM regimes from the last 20 years evaluated with the original Strickland criteria (Table 5). Articles using other grading systems, such as Buck-Gramcko, TAM or modified Strickland were not included (Gerard et al., 1998, Riaz et al., 1999, Hung et al., 2005, Frueh et al., 2014). Comparison is difficult since the latter systems also include the MCP joint or demand less AROM for excellent or good gradings. The intervention groups from the comparative studies were included as well.

The first type of early active rehabilitation is a true EAM regime without rubber bands, using an extension block splint as in the original Belfast regime (Small et al., 1989). The second type is EAM combined with the Kleinert’s regime as mentioned above; we applied this method in our study. The third type of active rehabilitation comprise PAH. It is also referred to as EAM since the flexor tendons are loaded. However, the contraction of the flexor muscles does not lead to any motion of the fingers, indicating that PAH is not a true EAM regime. In all but one paper (Farzad et al., 2014) PAH was combined with rubber bands. We assessed the pooled results for these active rehabilitation groups and found 88% excellent or good function with true EAM, 88% with EAM combined with the Kleinert’s regime and 87% with PAH regimes. Our results with 82 % excellent or good function in the active group did not reach such a high rate, probably due to inclusion of mild crush injuries, which are associated with worse prognosis. However, our results are comparable to the 80% rate of excellent or good function that was accepted in previous reviews (Elliot, 2002, Tang, 2013).

The functional results seem to have improved slightly in the last decades (Wu and Tang, 2014). However, these results can still not compete with the results of Chow et al. (1988) using combined Kleinert’s and Duran’s rehabilitation (Washington regime). They reported 76/78 (98%) excellent or good gradings and 3/78 (4%) rupture rate, challenging every later publication. However, other publications with combined Kleinert and Duran protocols could not achieve such outstanding results. A recent systematic review showed
that this combination and the EAM protocols exhibited higher proportions of digits with excellent or good results than the Kleinert’s or Duran’s regimes alone; however, it could not prove the superiority of EAM compared to the combined Kleinert and Duran protocols (Chesney et al., 2011).

Complications and reoperations

The rupture rate was 15/356 (4%) in Paper 3, and 1/34 (3%) and 2/39 (5%) in the Kleinert and active group, respectively, of Paper 4; these are within the range (4-5 %) acknowledged in the literature (Elliot, 2002, Dy et al., 2012). Our important finding is that the incidence of ruptures did not increased with use of EAM, probably due to a stronger repair technique.

The pooled rates of rupture in our literature review (Table 5) were 4%, 4% and 2% in the publications on true EAM, EAM + Kleinert’s and PAH regimes, respectively. PAH regimes have generally lower rupture rate, since active hold does not load the repair as much as active finger flexion exercises. A recent systematic review showed a 2.3% rupture rate with the Washington regime (Chesney et al. 2011), which is the rehabilitation with the lowest strain; however, it requires the most efforts from the therapists.

Paper 1 implied that the Yotsumoto-Dona suture is strong enough to withstand the loads under active finger flexion. Since the ruptures in Paper 4 occurred after removal of the splint, we cannot assume association with the loads under the early phase of rehabilitation, irrespective of which regime that was used; sudden unexpected overload was identified in all cases. However, in Paper 3 we observed four ruptures during the period of splint protection, in conjunction with the modified Kessler repair and Kleinert’s regime. In these cases, we can assume that the patients either unintentionally or consciously flexed their fingers actively, leading to overload of the repair. In patients with questionable cooperation a stronger repair may resist the overload when they “try out” their repairs, despite the recommendations of the therapists. The rupture rate was higher (5-46%) in publications on EAM rehabilitation after traditional Kessler suture, and the majority of ruptures occurred during the first three postoperative weeks (Small et al., 1989, Cullen et al., 1989, Bainbridge et al., 1994, Peck et al., 1998, Braga-Silva and
Kuyven, 2005). By using stronger repair techniques the rate of rupture decreased to the acceptable 4%, and often followed after removal of the protecting splint.

Other observed complications in our clinical studies were delayed wound healing and superficial infections, mostly in association with POS. Transitory swelling and tenderness over the tendon sheath were found in combination with the Yotsumoto-Dona suture, maybe a consequence of the complex epitendinous suture; all resolved without further surgical intervention. Granulomas were found both in Paper 2 and 3 in association with POS and Kessler suture, but were not present in Paper 4 (Yotsumoto-Dona suture). Other rare complications, unspecific to flexor tendon repair comprised carpal tunnel syndrome, hypertrophic scar formation and complex regional pain syndrome.

Most of the ruptured tendons were re-repaired immediately. The incidences of re-repair were 15/356 (4%) in Paper 3, and totally 3/73 (4%) in Paper 4. According to Paper 3 our frequency of tenolysis was 4% (14/356), which is similar to previous observations (Dy et al., 2012a). It is difficult to define the difference between decreased AROM and clinically significant adhesion or contracture. However, tenolysis or arthrolysis could be considered in fingers with compromised function that do not improve after prolonged therapy. In cases where further reconstructive surgery was unrealistic, and if stiff fingers in bad position compromised hand function, salvage procedures were considered. Tenodesis or joint fusion was carried out in 8/356 cases (2%), and amputation in one.

Conclusion about flexor tendon repair strategies

In the treatment of flexor tendon injuries, one should choose the appropriate combination of repair method and rehabilitation. A finger with a weak repair (modified Kessler) mobilized with a high load regime (EAM) is prone to rupture. On the contrary, a tendon repaired with high strength and high friction technique (multistrand or complex epitendinous suture) could probably not glide properly when combined with a low strain (Kleinert’s or Duran’s) mobilization. The most conservative strategy, the use of a low strength and low friction repair (modified Kessler suture) combined with a low strain mobilization (combined Kleinert’s and Duran’s regime) could lead to acceptable clinical results (73% excellent or good) and a low rupture rate (2%) (Chesney et al., 2011).
Adequate supervision by a therapist with frequent follow up consultations is a prerequisite for this strategy.

When a high strength – high friction repair (multi-strand or modern two-strand suture) is used, the increased gliding resistance should be overcome by a high strain rehabilitation (EAM). The clinical results with this strategy are good (88% excellent or good) with a slightly higher rupture rate (4%), but the same as previously accepted in the literature. PAH is considered a medium strain rehabilitation and could be combined with both low strength and low friction, or high strength and high friction repairs, anyway, the clinical results are good (87% excellent or good) and the rupture rate is low (2%).
4) LIMITATIONS

In Paper 1 we used porcine tendons, which are accepted models for human flexor tendons. The ultimate strength of the repair of human and porcine tendons are identical; however, the gap resistance of porcine tendons is higher (Hausmann et al, 2009). We should take into account the higher suture holding capacity of porcine tendons when interpreting the results. The measures of strength, especially the 2 mm gap force, would probably show lower values in human tendons despite identical experimental set up, which is limiting the transferability. However, porcine tendons are widely used in similar studies, and the results with different repair techniques on similar tendons are directly comparable to each other.

The clinical relevance of this study is obvious, as we found the Yotsumoto-Dona suture to be stronger than the traditional modified Kessler suture. However, since this is an ex vivo study it is difficult to predict the reactions occurring in the living organism. These results apply only the “time zero” strength. We do not know the different development of the two methods during the healing process, with respect to strength, tissue reaction and gliding resistance.

The weakness of Paper 2 is the retrospective design. This is a non-randomized quasi experiment, which is very prone to selection bias because the method used was the surgeons’ choice. Despite the small sample size, we were able to show significant functional superiority of the TILT method at 8 weeks. The difference was less at the last follow up, maybe an effect of the limited sample size. Another effect of the small sample size was that one case with inferior results could diminish the significance and lead to type 2 error. This study is highly clinically relevant. After evaluating the results, we found it unnecessary to perform any further investigations before implementing TILT as our new routine.

The statistical method we used in Paper 3 has limitations. A requirement for regression analysis is the independence of observations. We cannot assume that the results for each finger are really independent in case of multiple finger injuries. However, the localization and the extent of the injury can vary between adjacent fingers. We often observed different function or need for reoperation in various fingers of the same patients, implying some degree of independence. In similar publications, the results are
usually analyzed by finger and not by patient, as we also did in Papers 3 and 4. The adjusted R-squared values of our statistical models in Paper 3 are relatively low; other unknown predictor variables or interactions could influence the models. As the highest R-squared value of our models was 0.471, we could not explain more than 47% of the variations in the observations.

The identified predictors showed large differences in effect. Associated fracture had approximately 100 times higher regression coefficient (34.5) than delay of surgery (0.3). However, age and delay are continuous variables and their coefficients (0.47 and 0.3, respectively) should be multiplied by the actual value of these variables. 50 years of difference in age corresponds to an AROM difference of 24 degrees, comparable with other strong predictors like associated fracture, localization to subzone 1c-2c, weaker repair technique and smoking, which reduce the predicted 8 weeks AROM with 35, 26, 21 and 17 degrees. These variables have similar coefficients in all models, and their effects are additive. That means a 50-year-old smoking patient with a tendon injury within the narrowest part of the sheath associated with a fracture and repaired with a Kessler suture can expect a 123 degrees reduction of the 8 weeks AROM. In our material, delay of surgery had a very low effect; a delay of two weeks would decrease the AROM with only 4 degrees. The previously mentioned factors had much stronger effect; in a case without those reductions, the effect of delay is minimal. It complies with our clinical experience that a young, non-smoking patient with injury outside zone 2 and a strong repair could expect good clinical results despite 2-3 weeks delayed surgery.

Some predictors were relevant only in particular zones, such as the treatment of the sheath/pulley, the extent of the injury and the condition of the FDS tendon. Other factors were also associated with specific localizations, without obvious correlation to specific anatomical relationship. Injury of the little finger was an insignificant negative predictor in the zones 1 and 2, both at 8 weeks and at the last evaluation, with 9 and 12 degrees of reduction, respectively. On the contrary, the extent of soft tissue damage had effect only in the zones 2 and 3 with 4 and 5 degrees of reduction per increase in stage, respectively, to mild or moderate crush; however, this effect was also insignificant. Including these insignificant predictors in the models could increase the probability of type I error. However, their use strengthened the statistical models’ ability to explain the
observations. Since they were relevant in both the 8 weeks and final evaluations, their inclusion in the models is considered important despite the high p values.

Paper 3 was affected by a selection bias. Complications or the need for further treatment often prolonged the follow up. Many cases with satisfactory functional progress at 8 weeks were not routinely called back for further follow up. Hence the last recorded AROM may have been poorer than what could have been recorded later, because the function of injured fingers can improve for up to one year after surgery (Elliot, 2002, May and Silfverskiöld, 1993, Moriya et al, 2015). The short follow up may explain the inferiority of our functional results compared with other reports where all patients were called back for late evaluations. However, our intention was not to report how well we treat these injuries, but to analyse the possible causes of the variation in results. The function improves with time. With the same long follow up of all cases, the functional results would probably be less differentiated, making the same statistical analysis less robust.

The main limitation of Paper 4 is the lack of blinding. Neither the patients nor the evaluating therapists were blinded to the method used. It was practically impossible, as the same therapists were also involved in the rehabilitation of the patients. We consider knowledge of the regime quite unlikely to affect the objective measurements. There was no other difference in the treatment of the groups than flexing their fingers actively or passively.

Since informed consent was gained from the participants, they were informed about the two alternative treatments. This was no problem in the active group, as they were treated with the method entailing the fewest restrictions. The Kleinert patients knew that their repair should withstand active finger motion, which they were persuaded to avoid. We tried to avoid direct contact between the patients with different regimes during the first four weeks. It is not certain that the Kleinert patients did not flex their fingers actively, which could have affected their functional results.

Our intention was to minimize the difference between the two groups. Therefore, we used EAM combined with the Kleinert’s regime. Our long-term results did not differ significantly. Probably other, real EAM regimes could lead to different results, but this would also involve several other differences between the groups than simply allowing active flexion or not.
CONCLUSIONS

1. Yotsumoto-Dona suture is stronger than modified Kessler suture.

2. Yotsumoto-Dona suture is strong enough to withstand the loads under early active mobilization.

3. Transverse interosseous loop technique is superior to pull-out suture for tendon reattachment in respect to both the functional outcome and complications.

4. Age, smoking, injury localized to or between the A2 and A4 pulleys (subzones 1c to 2c), injury of the little finger, extent of soft tissue damage and concomitant skeletal injury are important negative predictors of functional outcome after flexor tendon repair in the zones 1, 2 and 3.

5. Stronger suture technique, repair of concomitantly severed superficial flexor tendons, limited release of conflicting pulleys, refraining from repairing the tendon sheath and early active mobilization of operated fingers can improve the outcome after flexor tendon repair in the zones 1, 2 and 3.

6. Adding active finger flexion exercises to dynamic splint treatment can accelerate the functional recovery; however, probably not significantly improve the long-term outcome after flexor tendon repair in the zones 1, 2 and 3.
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