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In vivo flexor tendon forces generated during different rehabilitation exercises

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Abstract

We measured in vivo forces in the flexor digitorum profundus and the flexor digitorum superficialis tendons during commonly used rehabilitation manoeuvres after flexor tendon repair by placing a buckle force transducer on the tendons of the index finger in the carpal canal during open carpal tunnel release of 12 patients. We compared peak forces for each manoeuvre with the reported strength of a flexor tendon repair. Median flexor digitorum profundus force (24 N) during isolated flexor digitorum profundus flexion and median flexor digitorum superficialis force (13 N) during isolated flexor digitorum superficialis flexion were significantly higher than during the other manoeuvres. Significantly higher median forces were observed in the flexor digitorum superficialis with the wrist at 30° flexion (6 N) compared with the neutral wrist position (5 N). Median flexor digitorum profundus forces were significantly higher during active finger flexion (6 N) compared with place and hold (3 N). Place and hold and active finger flexion with the wrist in the neutral position or tenodesis generated the lowest forces; isolated flexion of these tendons generated higher forces along the flexor tendons.

Level of evidence: III (controlled trial without randomization)

Keywords

Flexor tendon, force, in vivo, rehabilitation, repair

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Introduction

Intrasynovial flexor tendon injuries in the hand are often complicated by formation of peritendinous adhesions. Both advanced suture techniques and an adequate postoperative rehabilitation regime are fundamental to prevent adhesions, rupture of the repair, finger stiffness and decreased tendon gliding (Tang, 2006; Tang, 2013). Early controlled tendon mobilization prevents adhesion formation, improves tendon healing and digital ranges of motion (Moriya et al., 2015; Strickland and Glogovac, 1980; Wada et al., 2001). Despite these efforts, 4%–18% of repaired tendons rupture (Su et al., 2005; Tang, 2005). Excessive stress and high force during finger motion may cause gap formation and eventually rupture of the repair (Gelberman et al., 1999; Rodger et al., 2015; Zhao et al., 2004). Rehabilitation exercises should ideally apply enough force on the tendon to induce excursion without causing gap formation.

Numerous rehabilitation regimens are in use today. There are, in principal, three types of early rehabilitation programs: early passive mobilization with active extension-passive flexion with rubber bands to maintain the involved fingers in flexion (Kleinert et al., 1973) or passive flexion and extension supplied by the patient (Duran and Houser, 1975); active hold (i.e. place and hold) where the patient passively flexes the fingers and maintains them actively in flexion (Silfverskiold and May, 1994; Strickland, 1995); and early active motion with the patient actively flexing their treated fingers (Elliot et al., 1994; Small et al., 1989). Active mobilization protocols may have a higher risk of rupture of the repair, while passive protocols may have a higher risk

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Figure 1. The buckle force transducer with frame and fulcrum. (A) The tendon aligns in the semicircular arches of the frame and rests on the removable fulcrum. (B) The tension in the tendon created during finger movements passes over the fulcrum, which creates a bending load on the frame. Four silicon strain gauges placed on opposite sides of the frame measure and summarize the bending load on the frame.

of tendon adhesion and loss of digit range of motion. No consensus exists concerning the best type of motion or the ideal hand posture during rehabilitation (Starr et al., 2013).

A better understanding of actual forces generated in the flexor tendons during various commonly used rehabilitation manoeuvres with different wrist positions is needed to design rehabilitation protocols that allow maximal tendon gliding without causing rupture of the repair. Although in vivo flexor tendon forces and the relationship between force at the fingertip and force at the tendon have been measured (Dennerlein et al., 1999; Powell and Trail, 2004; Schuind et al., 1992), tendon forces during clinically relevant rehabilitation protocols were not described in these studies.

The aim of this study was to measure the forces produced in vivo in the flexor digitorum profundus (FDP) and the flexor digitorum superficialis (FDS) tendons during commonly used rehabilitation exercises.

Methods

Twelve patients (eight females and four males) with a mean age of 42 years (range 32–52), volunteered to participate in the study. The patients had no other upper extremity disorders or systemic disease. The study procedure was conducted in the Outpatient Surgery Center during open carpal tunnel release. Surgery was performed on the dominant hand of seven patients (six right and one left) and on the non-dominant hand of five patients (five left).

Technique

At a standard open carpal tunnel release under local anaesthetic with tourniquet control, the FDP and FDS tendons of the index finger were identified and, as previously described (Kursa et al., 2006), two gas-sterilized buckle force transducers were mounted, one on each tendon (Figure 1(A)). The transducer consists of a $9 \times 16 \times 4.5$ mm stainless steel frame and a removable fulcrum designed to fit easily inside the carpal canal and to move with the tendons without interfering with tendon movements or adjacent structures. The transducers are a modified version of the method described by Dennerlein et al. (1997). The modified transducer has four silicon strain gauges instead of two, to increase the measurement sensitivity of forces transmitted in the tendon by summing bending load from both sides of the frame (Figure 1(B)). The transducers were staggered in order to avoid interfering with each other. The tendons with the transducers were then allowed to slide back into the carpal tunnel. The patient flexed their index finger against a load 20 times to ensure that the transducer was well coupled with the tendon. Data were collected from the tendon transducers at 100 Hz using a laptop computer with an A/D board (DAQCard-AI-16E-4, National Instruments, Austin, Texas, USA). Transducer output to tendon force was calculated for each transducer (mean error 3.8%–7.3%). To allow adjustment for tendon thickness on transducer output to tendon force, the thickness of the tendon was measured with a custom calliper after seating and while in the transducer (Series 575, Absolute Digital Indicator, Mitutoyo, Kawasaki, Japan).

The patients were supine during the procedure, with the shoulder abducted to 90° and the forearm neutral with the hand positioned with the thumb up and the palm facing the feet. The surgeon marked the centres of joints rotation of the index finger and wrist with a surgical pen. A digital video camera (DCR-TRV10, Sony, Tokyo, Japan) was positioned above the operating field, perpendicular to the plane of finger flexion, recording the radial side of the hand (30 frames/s) where the joints' centres were marked. Each manoeuvre was repeated until two trials were performed appropriately. To minimize differences in manoeuvres between patients, the surgeon guided the patients through the rehabilitation manoeuvres during the experiment. The tourniquet was released to allow tissue reperfusion 20 minutes before data collection.

Five rehabilitation manoeuvres were studied.

1. Place and hold – The surgeon passively flexed all fingers from a fully extended position to a fully flexed posture (full fist). The patient maintained the fingers actively in a flexed position for 3 seconds before actively extending them to the fully extended starting point.
2. Active finger flexion – The patient actively flexed all fingers from a fully extended position until their fingertips lightly touched their palm, maintained the fully flexed position for 3 seconds before actively extending the fingers to the fully extended starting point.
3. Isolated FDP flexion – The patient actively flexed the FDP tendon alone while the surgeon immobilized the FDS tendon by holding the middle phalanx with the metacarpophalangeal and proximal interphalangeal joints extended.
4. Isolated FDS flexion – The patient actively flexed the FDS tendon of the index finger alone while the surgeon immobilized the FDP tendons by holding the other three fingers in full extension.
5. Tenodesis – The surgeon passively flexed and extended the wrist causing finger flexion and extension.

The first four manoeuvres were repeated with the wrist in both a neutral position (0° flexion) as well as in 30° flexion, as some patients with sutured flexor tendons have a dorsal cast with the wrist flexed and are instructed to leave the dorsal cast on while initiating rehabilitation. The flexed position was achieved by holding the dorsal side of the patient's hand and forearm against a sterilized angle bracket. After completing the manoeuvres, the transducers were removed and the incision closed. The surgeon who performed the operation reviewed the videotapes after each experiment to confirm that the manoeuvres were performed correctly and that they simulated rehabilitation exercises used in a hand clinic. Blinded to the force data, the trial that best represented the desired motion was selected for analysis.

Statistical analysis

The force data was synchronized with the video and peak forces for each manoeuvre were extracted. To identify significant differences in peak forces for FDP and FDS tendons, a two-factor (i.e. manoeuvre and wrist posture) repeated measures analysis of variance was used. The force data was log-transformed in the analysis of variance to more closely follow a normal distribution. Tukey's follow-up test was used to test for differences of individual factor levels. The analysis was not done for dominant versus non-dominant hand because the force measurement already adjusts for tendon thickness and the analytical power would be too low.

The Committee on Human Research approved the study and the participants provided a written consent prior to the procedures.

Results

Peak forces measured in the FDP and FDS tendons during five rehabilitation manoeuvres at two wrist angles are presented in Table 1. There was no significant statistical interaction between wrist posture and manoeuvre. The tenodesis manoeuvre was not included in the analysis because it could not be assigned a wrist posture.

The highest median peak force (26 N) for the FDP tendon was created during isolated active FDP flexion with wrist in neutral. The highest median peak force (14N) for the FDS tendon was created during isolated active FDS flexion with the wrist flexed. The lowest median FDP and FDS peak forces (3N, respectively) were observed during tenodesis (Table 1).

For both wrist postures, median peak FDP force (24 N) during isolated FDP flexion was significantly higher than with place and hold (3 N), active finger flexion (6 N) and isolated FDS (3 N); median peak FDS force (13 N) during isolated FDS flexion was significantly higher than with place and hold (6 N), active finger flexion (3 N) and isolated FDP flexion (4 N) (Table 1).

Wrist posture significantly affected the FDS tendon forces ($P=0.03$), but not the FDP tendon forces. Higher forces were generated in the FDS tendon with the wrist at 30° flexion (6 N) compared with the neutral wrist position (5 N). Similar forces were recorded in the FDP tendon at both wrist postures. Forces in the FDP tendon (6 N) during active finger flexion were

Table 1. Peak tendon forces at different wrist positions.

Forces recorded	Place and hold		Active finger flexion		Isolated FDP flexion		Isolated FDS flexion		Tenodesis
	Wrist neutral	Wrist flexed	Wrist neutral	Wrist flexed	Wrist neutral	Wrist flexed	Wrist neutral	Wrist flexed	
Peak FDP forces (N)									
Mean	3.6	3.1	6.5[a]	5.9	25.5[b]	23.8[b]	3.1	2.9	2.8
SD	3.1	2.8	5.1	4.7	20.4	19.6	5.2	7.5	4.8
Maximum	10.6	10.1	17.3	17.8	73.8	74.7	16.0	22.7	15.8
Peak FDS forces (N)									
Mean	4.9	7.7[c]	2.9	3.5	4.3	4.2	12.9[d]	14.1[d]	2.7
SD	2.6	5.6	6.7	12.9	3.1	5.1	6.4	8.0	1.0
Maximum	10.9	23.7	25.6	47.5	12.9	20.0	24.2	32.9	4.6

[a]Compared with place and hold ($p < 0.001$).
[b]Compared with other three hand actions (except tenodesis) with wrist in either position ($p < 0.001$).
[c]Compared with wrist neutral position ($p = 0.03$).
[d]Compared with other three hand action (except tenodesis) with the wrist in either position ($p < 0.001$).
FDP: flexor digitorum profundus; FDS: flexor digitorum superficialis.

significantly higher than during place and hold (3 N) ($P < 0.001$) (Table 1).

Discussion

We recorded the highest median forces during isolated FDP and FDS flexion. These manoeuvres are used to allow gliding of only the tendon that is activated, but unexpectedly, forces up to 23 N were observed in the other tendon during the isolated tendon manoeuvre. Those peak forces could exceed repair strengths in some patients. Since isolated FDP and FDS flexion create high forces on the tendons but low excursions between the tendons (Sapienza et al., 2013), they should be avoided during rehabilitation.

Active finger flexion generated significantly higher forces in the FDP tendon compared with place and hold. The place and hold manoeuvre is believed to minimize the force on the tendon compared with active finger flexion. However, the forces in the FDS tendon tended to be higher during place and hold. We recorded large differences in the FDP tendon forces between patients. These differences may be due to differences in motor control or joint stiffness. The FDP tendon to the index finger is separated, whereas the tendons to the middle, ring and little fingers are conjoined. This anatomical difference might affect forces generated by the tendons to ulnar fingers.

Previously we have shown significantly higher forces in the FDS tendons with the wrist at 30° flexion compared with the neutral wrist position, but no significant differences in the FDP tendons (Kursa et al., 2006). The present analysis confirms these findings. We recorded significantly higher forces in the FDS tendon at 30° wrist flexion. FDP tendon forces were similar at both wrist positions. The current position of postoperative wrist flexion to protect the tendon repair may be harmful rather than beneficial by increasing FDS tension.

Nelson et al. (2012) found that the number of core suture strands significantly increases repair strength compared with other variables. Miller et al. (2007) and Vigler et al. (2008) reported mean ultimate strengths of 49–124 N and 52–85 N, respectively, for different 4-strand repairs. Xie et al. (2002) compared three different 6-strand suture techniques and found mean ultimate strengths between 51 N and 60 N. Osei et al. (2014) stated mean ultimate strengths of 49–57 N for 4-strand repairs and 82 N for an 8-strand repair. It is essential that the repair withstand forces generated during early mobilization, both initially and following early tendon softening. The mean repair strengths during the first postoperative 10 days vary between a decrease of 18%, to an increase of 25% compared with initial strength (Aoki et al., 1997; Boyer et al., 2001; Hatanaka et al., 2000; Wada et al., 2001). Hatanaka et al. (2000) described a non-significant decrease in tensile strength between 0 and 7 days following tendon repair using a passive mobilization protocol, and a significant increase by Day 21. Boyer et al. (2001) demonstrated no significant changes in strengths from before Day 21, but a significant increase between Days 21 and 42. Thus, during the first 3 weeks, a safety factor of an 18% decrease in repair strength should be considered. Before rupture of the repair, a gap forms, which impairs tendon excursion and may lead to rupture (Gelberman et al., 1999; Zhao et al., 2004). Gaps of 2 mm are seen at approximately 70% of the ultimate repair strength (Miller et al., 2007; Osei et al., 2014;

Vigler et al., 2008; Xie et al., 2002). A safety factor of an additional 30% should therefore be deducted from the ultimate strength to account for gapping.

Various 4-strand repairs withstand ultimate forces of 49–85 N (Barrie et al., 2000; Miller et al., 2007; Osei et al., 2014; Vigler et al., 2008; Viinikainen et al., 2004), and 6-strand repairs 51–76 N (Viinikainen et al., 2004; Xie et al., 2002) before repair failure. After deducting a safety factor of 18% decreased repair strength and 30% for gapping, we estimate that peak forces on the flexor tendon during rehabilitation should be less than 28 and 29 N for 4-strand and 6-strand sutures, respectively. Based on the data from this study, we recommend active finger flexion and place and hold with the wrist in neutral, as well as tenodesis during the first 3 weeks after a 4- or 6-strand surgical repair of the FDP or FDS tendons. Isolated FDP and FDS flexion should be avoided or used with caution during the first 3 weeks post-operatively. None of the tendon forces exceeded 28 N with this recommended rehabilitation method. Nine patients exceeded 28 N during isolated FDP flexion, one patient exceeded 28 N during isolated FDS flexion and one patient exceed 28 N during active finger flexion with the wrist in a flexed position.

Forces in the FDP tendon are significantly higher during active finger flexion compared with place and hold, but they do not exceed the strength of a standard 4- or 6-strand repair. However, depending on the initial injury, the patient and the repair, some patients may need to limit tendon forces and they may therefore be best advised to avoid active finger flexion during the first 3 weeks after surgery. We recommend a plaster or splint with the wrist in neutral to reduce FDS tendon tension.

There are limitations in this study: there is only a small sample size; intact rather than injured tendons were tested; there were no recent finger injuries that could increase tendon gliding resistance through swelling and adhesions (Wu and Tang, 2013, 2014). Partial active finger flexion has been used in recent years after surgery to reduce the forces over the tendon repair and is replacing full range of active motion protocols in the first 3 or 4 weeks (Lalonde and Martin, 2013; Tang, 2007). We did not include measurement of forces at partial finger flexion into this study; we did not measure tendon forces during wrist extension. The effect of wrist angle on tendon forces has previously been evaluated, but with inconsistent findings (Lieber et al., 1996; Savage, 1988).

In conclusion, active finger flexion and place and hold with the wrist in neutral or tenodesis limit the risk of repair rupture after a 4- or 6-strand surgical repair of FDP and FDS tendons. Isolated FDP and FDS flexion should be used with caution due to higher measured tendon forces and lower excursion.

Conflict of interests

None declared.

Ethical approval

The Committee on Human Research from the University of California, San Francisco, approved the study, and the participants read and signed a consent form prior to the procedures

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