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Short-term Assessment of Optimal Timing for Postoperative Rehabilitation after Flexor Digitorum Profundus Tendon Repair in a Canine Model

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Abstract

The purpose of this study was to compare the shortterm outcome following flexor tendon repair for postoperative rehabilitation commencing on day 1 (a common clinical choice) versus day 5 (the day on which, with postoperative immobilization, the initial gliding resistance is least in this model) in an in vivo canine model. Work of flexion (WOF) and tendon strength were evaluated following tendon laceration and repair in 24 dogs sacrificed 10 days postoperatively. Starting postoperative mobilization at day 5 resulted in no tendon ruptures compared with tendon ruptures in four of the dogs (33%) in the group subjected to mobilization starting at day 1. While there was no statistically significant difference in WOF between groups at day 10, there was a trend toward lower resistance favoring the day 5 start group, and the statistical power to detect a difference in WOF was diminished by the ruptures in the day 1 group. We conclude that starting rehabilitation on day 5, when initial gliding resistance is lower, may have an advantage over earlier starting times, when surgical edema and other factors increase the initial force requirements to initiate tendon gliding. We plan further studies to evaluate the longer-term benefits of this rehabilitation program.

Until the mid-1960s, most flexor tendon repairs were immobilized postoperatively for at least three weeks. This policy was based on the research of Mason and Allen,¹ who showed that flexor tendon tensile strength decreased for three weeks after repair in a canine model. Subsequently, many clinical and animal studies have demonstrated that early mobilization after tendon repair has many beneficial effects, such as increased tendon excursion, decreased adhesion formation, and increased tensile strength.^{2–5} Now, it is universally accepted that postoperative rehabilitation should begin soon after flexor tendon repair.^{6–9} However, postoperative mobilization can be complicated by gap formation or tendon rupture, which can impair the outcome.^{10–12}

The safe zone in which postoperative mobilization can be performed is bounded by the strength of the repaired tendon, which represents the upper limit of force that can be applied to the tendon during mobilization, and the resistance of the digit to motion, which is the lower limit that must be overcome during rehabilitation for tendon motion to occur. Ideally, one would want to initiate postoperative mobilization at a time when this safe zone is relatively wide, to include a margin of safety. The upper limit, repair strength, has been well studied. Many tendon

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repair techniques have been described both clinically and experimentally,^{13–17} and many mobilization strategies have been designed around repair strength.¹⁸ However, little information is available on the lower limit, digit resistance after tendon repair (measured by work of flexion [WOF]), especially in the critical first days after repair, when mobilization typically begins. The rough surface and bulk of a repaired tendon, surrounding soft-tissue edema, increased joint stiffness, and, later, the presence of adhesions, all increase the resistance of the digit to postoperative motion.

While the use of active motion can inform the therapist whether tendon motion is occurring,¹⁸ this method runs the risk of exceeding the repair strength, as the patient contracts harder and harder to try to achieve digit motion. This is especially true early in the postoperative period, when the tendon may also need to move a stiff, swollen finger. Ideally, postoperative mobilization should be initiated when the therapist has the widest margin of safety between the tendon's breaking strength and the load required to initiate tendon gliding within the sheath. There are currently little clinical or research data on which to base such a decision. Halikis et al.¹⁹ used a chicken model to study the issue of timing of postoperative mobilization initiation, and concluded that results were improved when a delay of three days was imposed before initiating mobilization, as compared with mobilization commencing on the day after surgery. However, in that study the chickens were analyzed only at three and seven days postoperatively; because other intervals were not studied, it is possible that some critical data supporting the use of other start times may have been overlooked. In a prior study using a canine model,²⁰ we studied additional time points (one, three, five, and seven days), and found an optimization point at day 5 postoperatively, when the difference between tendon strength and gliding resistance was greatest. Therefore, the purpose of the current study was to confirm if the postoperative day 5 is the optimal timing point for initiating postoperative mobilization compared to mobilization initiated on postoperative day 1 (a clinically and experimentally popular starting date^{21–25}), as validated by shortterm outcomes including repair integrity, strength, and WOF, using a canine model in vivo.

MATERIAL AND METHODS

Previous Study

In a prior study,²⁰ 48 mixed-breed dogs, weighing from 20 to 25 kg, were studied to compare the mechanical properties of repaired flexor tendons at one, three, five, and seven days postoperatively by analyzing the gliding resistance data ($n = 12$ dogs per time point). We reanalyzed the experiment data of this study to calculate the WOF, and thereby compare the data obtained in the current study with the previous work. (See following data analysis.) By combining data in this way, we were able to significantly reduce the number of experimental animals needed to complete this study.

Work of flexion was evaluated in 144 digits and tendon strength was evaluated in 48 digits. In each dog, WOF was measured in a repaired tendon, a sham-operated tendon (wound was immediately closed after tendon exposure without tendon laceration), and a normal unoperated tendon. After surgery, the paw and forearm were dressed and immobilized with waterproof casting tape to maintain 45-degree wrist flexion and neutral position of the digit joints for the entire time period.

Current Study

In the current study, 24 mixed-breed dogs weighing 20 to 25 kg were used and randomly divided into two groups. In the first group (10A), the postoperative mobilization started at day 1, and the second group the mobilization started at day 5 (10B) postoperatively. In one forepaw, the second and fifth digits were randomized for repair and sham operation and WOF was evaluated

while the third digit was repaired and subjected to strength testing. The postoperative rehabilitation protocol used was passive flexion/extension of the digit with the wrist in 45 degrees flexion.³ Rehabilitation was performed twice daily. All dogs were killed at day 10.

Operative Procedure

The project was reviewed and approved by our IACUC, and all NIH animal care guidelines were followed. The dogs were anesthetized with intravenous ketamine (13 mg/kg) and diazepam (6 mg/kg) and maintained under anesthesia with 1.5% isoflurane. The selected forepaw was shaved, scrubbed with povidone-iodine, and sterilely draped. A radial neurectomy proximal to the triceps innervation was performed first, to prevent postoperative weight-bearing on the operative limb. An elastic bandage was then used to exsanguinate the forelimb and act as a tourniquet for the procedure. The flexor digitorum profundus (FDP) tendon (in either the second or fifth digit and the third digit) was approached through a midlateral incision in the paw between the proximal and distal annular pulleys. The FDP tendon was then sharply transected 5 mm proximal to the distal edge of the proximal pulley, with the digit extended. The tendon was then repaired with a modified Kessler technique, which has been commonly used both clinically and experimentally. The suture of the repair was 4/0 looped Supramid (S. Jackson, Inc., Alexandria, VA); therefore, the repair was a four-strand repair. A simple running circumferential epitendon suture of 6/0 nylon (Ethicon Inc., Somerville, NJ) was used to reinforce the repair. The sham digit wound was closed immediately after tendon exposure. The paw and forearm were dressed and immobilized with waterproof casting tape to maintain 45-degree wrist flexion and neutral position of the digit joints after surgery.

Digit Resistance Test

Specimen Preparation—At the time of death, the operated forelimb was disarticulated at the elbow. The digits were transected at the midmetacarpal level. The FDP tendon was divided at the wrist level and the FDS tendon was cut more distally, so as not to interfere with the profundus stump. A K-wire was inserted longitudinally through the metacarpal bone to fix the metacarpophalangeal joint in extension. The FDP tendon was divided from its insertion on the distal phalanx. The distal vincula was carefully transected without interfering with the repair site. The proximal third of the distal phalanx was removed and a small load transducer (BG-1000G, Kulite Semiconductor Products, Inc., Leonia, NJ) was fixed to the remaining distal phalanx with a screw. The distal end of the FDP tendon was then connected to this transducer by a cable (Figure 1).

Testing Device—The testing device consisted of a testing frame, actuator, linear potentiometer, and two load transducers. One of the transducers had already been fixed to the distal phalanx described above. A 0.5-N weight was attached to the extensor tendon to ensure full extension of the digit for a starting position, and to apply an initial tension to the FDP tendon. The proximal end of the FDP tendon was connected to a second load transducer which was then connected to the actuator and linear potentiometer (Figure 1). A 0.1-N preload was applied to the proximal tendon before testing. The actuator pulled the FDP tendon proximally at a rate of 2mm per second, causing digit flexion. Tendon excursion and proximal and distal tendon force were recorded during testing. Videofluoroscopy was used to simultaneously record the digit motion. The fluoroscopic images were digitized to obtain the joint motion of the proximal (PIP) and distal interphalangeal (PIP) joints (Figure 2).

Data Analysis

During digit flexion, the presence of friction between the tendon and sheath will cause the proximal tendon force to be larger than the distal tendon force. Thus, the proximal force reading is the total amount of force needed to flex the digit and the area under the proximal force versus

tendon excursion curve will be the total work needed for flexion (TWOF) (Figure 3). The amount of energy expended due to friction and other forces of the tendon-sheath interaction can be termed the internal work of flexion (IWOFF). Because the amount of total force that gets transferred to the distal phalanx is recorded by the distal load transducer, the IWOFF can be calculated as the area between the proximal and distal force readings when plotted versus tendon excursion. Because the total arc of DIP motion between digits was variable, but always exceeded 40 degrees, the point when the DIP flexion of 40 degrees was used as an arbitrary endpoint for excursion (Figure 3). Because the proximal interphalangeal joint motion was also variable, although less so, the WOF was normalized by dividing by the total combined PIP and DIP joint motion in degrees.

Suture Strength Test—The repaired FDP tendon from the third digit was dissected free, fixed in clamps with interdigitating grooves, and tested to failure at a rate of 20 mm/min in a servohydraulic testing machine (MTS, Minneapolis, MN). Gapping at the laceration site was measured with a differential variable reluctance transducer (DVRT; MicroStrain, Burlington, VT) attached to the tendon. The maximum force and the resistance to gap (linear slope of the force versus gapping curve) were measured.

Statistics—In this study, two-factor analysis of variance was used for comparison between the rehabilitation at day 1 and day 5. All statistical tests were two-sided, and results with P values less than 0.05 were considered significant. All analysis was conducted using SAS 8.2 (SAS Institute Inc., Cary, NC) and S-Plus 3.4 (MathSoft Inc., Seattle, WA) on a Sun 420r computer (Sun Microsystems Inc., Palo Alto, CA).

RESULTS

Prior Study

In the previous study, the TWOF at day 5 was significantly lower than that at 1, 3, and 7 days ($P < 0.05$) (Figure 4). The mean IWOFF in the control group was 17% of the TWOF. In the sham group, the mean IWOFF was 19% of the TWOF. In the repair groups, the IWOFF made up about 36% of the TWOF, which was significantly increased compared to either the control or sham groups ($P < 0.05$). The IWOFF at day 5 was significantly less than it was at day 7 ($P < 0.05$) (Figure 5).

Current study

Eight tendons from four dogs ruptured in the group that started mobilization on day 1 (10A group) postoperatively. No tendons ruptured in the group that started mobilization on day 5 (10B group). The mean TWOF of the repair group was 1.065 (range 0.17–2.78) and 0.690 (range 0.1–1.57) N-mm/degree for groups 10A and 10B, respectively, which was not significantly different ($P > 0.05$) (Figure 4). The IWOFF was 0.66 (range 0.01–1.37) N-mm/degree and was 62% of the TWOF for the 10A group. In the 10B group, the IWOFF was 0.45 (range 0.04–1.30) N-mm/degree and was 65% of the TWOF. There was no significant difference in IWOFF between groups 10A and 10B ($P > 0.05$) (Figure 5).

The TWOF and IWOFF of the repaired tendon in 10A and 10B group were significantly higher compared to the day 1, 3, 5, and 7 groups ($P > 0.05$). However, there were no significant differences among all timing points for the sham operated and normal tendon groups ($P > 0.05$).

In the suture strength testing the repaired tendons consistently failed through the laceration site by pullout of the suture through the tendon. There was no significant difference in resistance to gap formation or maximum breaking strength between the 10A and 10B groups in the current

study ($P > 0.05$) (Figure 6). Additionally these measurements in 10A and 10B groups were not significantly different from the results at days 1, 3, 5, or 7 in the previous study ($P > 0.05$).

DISCUSSION

In the current study, postoperative mobilization starting at day 1 seemed inferior to starting at day 5, in that there was a higher tendon rupture rate, suggesting that the increased loading necessary to mobilize the digits at this stage may exceed the tolerance of the repair. There was also a trend for increasing WOF in the day 1 start group. While this difference was not significant, the high rupture rate in the day 1 group reduced our statistical power to detect such a difference.

The results also showed that both groups exhibited a significant increase in total and IWOFF compared to any time point during the first week of tendon repair (i.e., the data in the previous study). These results suggest that, at least for this animal model, the interval from day 5 to day 10 may be critical in the evolution of adhesions, and that attention to the prevention of adhesions might be focused on this interval. However, over the first 10 days postoperatively, although there was a trend toward increased tendon strength and resistance to gap formation, these changes were not statistically significant.

Work of flexion has been used experimentally for evaluation of digit function in both in vivo and in vitro studies,^{26–29} and it measures the work needed to actively flex the digit. The WOF includes factors intrinsic to the tendon and sheath (IWOFF), as well as factors extrinsic to the tendon and tendon sheath that must be overcome. The IWOFF is a combination of the surface friction between tendon and sheath, the bulk effect due to fit of the tendon within the flexor sheath, and the incremental resistance resulting from adhesions. The extrinsic factors that must be overcome include joint stiffness, soft tissue resistance, the mass of the digit, and resistance of antagonist muscles.³⁰ In the normal state, the TWOF is very small.^{31–33} However, after flexor tendon injury and repair, the WOF dramatically increases due to increased gliding resistance,^{34–36} tendon and soft tissue edema,^{27,37,38} increased joint stiffness,^{19,39,40} and subsequent adhesion formation.^{41–43}

Postoperative rehabilitation is an effective method to prevent adhesion formation and improve functional outcome after flexor tendon repair.^{3,7} Postoperative mobilization can be classified as either active or passive, based on the force applied to the tendon.^{44,45} In active motion protocols, loading applied to the tendon must be great enough to overcome the TWOF, otherwise, the digit will not move. However, if the resistance to motion exceeds the repair strength, the repair will gap or rupture before motion occurs. In contrast, passive motion protocols where the external load is overcome by the therapist, the force applied to the tendon only needs to overcome the gliding resistance within the tendon sheath (IWOFF). Because the force applied to the tendon during the passive motion is small, the IWOFF becomes a critical factor, which must be lower than the tendon tension. Otherwise, the tendon will buckle during mobilization instead of glide, as shown by Horii et al.⁴⁶ Because active and passive therapies affect different components of the TWOF, we believe that independent evaluation of these sources of digit resistance (internal or external) is beneficial. Also, we believe that the communication between hand surgeons and therapists is essential to affect the outcome after flexor tendon repair, especially during the first week postoperatively. A clean wound with a good quality repair may impose less “afterload” on a repair, and have a better breaking strength, so that mobilization might begin sooner, and with more confidence; a ragged wound with a difficult repair might engender more caution, and a later start time. It is also important to remember that our day-5 benchmark is not only for a repair done under controlled circumstances, but also in an animal model. The role of patient cooperation (or lack thereof) cannot be assessed in our model, nor can differences in rates of wound healing between species.

In this study we have identified a factor which may increase the margin of safety, the time at which postoperative mobilization is initiated. From our previous study, the TWOF was significantly lower at postoperative day 5 than at times either earlier or later, making it an opportune time to begin mobilization. This timing is slightly different than that suggested by Halikis et al.,¹⁹ who advised three days, based on their study in a chicken model. The differences may relate to the different models, or to the types of repairs used, but it seems consistent that it is possible to start postoperative mobilization too soon, as well as too late. This is also consistent with the philosophy of graded mobilization after tendon injury espoused by Groth.¹⁸

The limitations of this study include that the postoperative rehabilitation was the traditional passive motion protocol, which might be conservative compared to active or synergistic protocols.^{43,45,47} Second, only a short-term (ten days) outcome was investigated. The longer-term (such as six weeks) effect is thus, not clear. Thirdly, the practical difficulties with rigidly scheduling for a postoperative day 5 start to mobilization would have to be considered, which likely would spur additional research topics, such as day 4 or day 6. Finally, because this study was performed in a dog model, there are certainly differences compared to the human clinical environment.

CONCLUSION

This study was performed in a relevant in vivo model of tendon injury, and builds on and is consistent with a large body of prior work. We have found that, after tendon repair, the total digit resistance was at its lowest on postoperative day 5. Commencing postoperative mobilization on day 5 was superior compared with starting mobilization on day 1. We therefore conclude that active postoperative mobilization should start on postoperative day 5, at least in this dog model. If a passive motion protocol is to be chosen, it should also start within five days after tendon repair.

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FIGURE 1. Testing device. 1. Actuator, 2. Proximal transducer, 3. Specimen, 4. Flexor digitorum profundus tendon (proximal and distal) 5. Distal transducer, 6. Weight, 7. Frame.

FIGURE 2.

*Image obtained by fluoroscopy during testing. The curved arrow shows the direction of digit flexion. Two metal beads were placed into the middle phalanx (two straight arrows). The angle between the axis of the pin inserted axially into the proximal phalanx and the axis between the two beads in the middle phalanx is the proximal interphalangeal joint angle (**A**). The axis connecting the two beads in the middle phalanx and the axis of the distal phalanx screw make up the DIP joint angle (**B**).*

FIGURE 3.

Excursion indicates the FDP tendon excursion from full finger extension to full flexion. The y-axis represents the force recorded by the distal (F_d) and proximal transducers (F_p). The area under F_p indicates the total work of flexion (TWOF), and the area between F_p and F_d represents the work expended within the flexor sheath (internal work of flexion, IWOF). The right y-axis represents motion of the PIP (gray line) and DIP (dashed gray line) joints. The vertical dashed line indicates the ending point of data collection (DIP angle = 40 degrees).

FIGURE 4.

Total work of flexion in control, shamoperated, and repair groups at days 1, 3, 5, and 7 in 10A (starting therapy on day 1) and 10B (starting therapy on day 5) groups.

FIGURE 5.

Internal work of flexion in control, sham-operated, and repair groups at days 1, 3, 5, and 7 in 10A (starting therapy on day 1) and 10B (starting therapy on day 5) groups.

FIGURE 6.

The maximum force to tendon failure and repair site stiffness measured by DVRT did not show any significant differences among timing points.