Resistance to Motion of Flexor Tendons and Digital Edema: An *In Vivo* Study in a Chicken Model

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Purpose: Tissue edema contributes to resistance to motion of flexor tendons during postsurgical exercises. We assessed edema formation and resistance of injured subcutaneous tissue and sheath to motion of the digital flexor tendon in a chicken model.

Methods: Ninety-four toes of 47 white Leghorn chickens were divided into 6 surgical groups and 1 nonsurgical control. Subcutaneous tissue and the sheath were incised, and the skin incision and the subcutaneous tissue were closed surgically. The toes were evaluated morphologically for severity of edema and tested for the force and work required to move the tendon. The evaluation time points were 1, 2, 3, 4, 5, and 7 days after surgery. Edema in the toes was scored according to severity and extent. The force and energy required to move the tendon were measured at the first and sixth cycles after cyclic loading in a testing machine with customized software and were statistically analyzed.

Results: The force and work increased progressively for the first 4 days, and were relatively consistent from days 4 to 7. The severity of edema peaked at the third and fourth days. At each postsurgical day, edema scores corresponded to increases in the force and work. The force and work were reduced drastically (30%–50%) after the first 6 cycles of toe motion.

Conclusions: Resistance to tendon motion increased for the initial 4 days after surgery and remained comparatively consistent from the fourth to the seventh days. The severity of digital edema peaks at the third and fourth postoperative days. Motion of the digits for several cycles greatly reduces the resistance to the subsequent movement. We believe that tendon mobilization should not necessarily be started within the initial postoperative days, the optimum time to begin probably is the period from the fourth to the seventh day after surgery, and that judgment of edema helps to determine how aggressive exercise should be. (J Hand Surg 2006;31A:1645–1651. Copyright © 2006 by the American Society for Surgery of the Hand.)

Key words: Flexor tendon, edema, tendon motion, postoperative exercise.

Mobilization of repaired flexor tendons disrupts adhesions and prevents stiffness of the hand after tendon surgery.[1–5] Resistance to postsurgical finger mobilization comes from friction of the tendon surface against the subcutaneous tissue or sheath, stiffness of joints and extensor tendons, resistance of soft tissues, the mass of the fingers, and the resistance of antagonist muscles.[6–9] The friction of the tendon and resistance of soft tissues relate to edema of both the tendon and surrounding tissues, trauma to surfaces of the tendon, and sutures within the tendon or over the tendon surface. Among these factors, edema after surgery together with healing responses of the subcutaneous tissue and sheath is present in all patients because of the necessary approach to lacerated tendons through incisions in the subcutaneous tissue and sheath.[7–9] Edema of both peritendinous tissues and tendons persists in the early period of tendon healing. This study investigated the resistance of injured subcutaneous tissue and sheath to flexor tendon motion and edema after surgery in a model of subcutaneous and sheath injuries in chicken toes.

Materials and Methods

Ninety-four toes from both feet of 47 white Leghorn chickens were used because of the similarity between the tendon structures of chicken toes and those of human digital flexor tendons.[10–13] The area between the proximal interphalangeal (PIP) joint and the distal interphalangeal (DIP) joint was chosen as the region of experimentation. This area corresponds to the middle part of the zone II flexor tendons of the hands.[13]

Experimental Groups and Surgeries

Chickens were randomly divided into 6 surgical groups and 1 nonsurgery control group. The toes medial to the long toes (the longest toe in the chicken is called the *long toe* in the literature[10–14]) in both feet were chosen as a model. These toes have tendon structures that are identical to the long toe, but its length is about 70% of that of the long toe.

The chickens that had surgery were anesthetized with an intramuscular ketamine injection (50 mg/kg body weight). A tourniquet with an elastic bandage was applied to the leg to control bleeding. The feet were scrubbed with povidone-iodine and draped in a sterile surgical field. In all of the experimental toes, a zigzag incision was made between the PIP and DIP joint levels for a consistent length of 1.5 cm. The plantar side of the digital flexor sheath was exposed through this incision and the sheath was incised for 1.0 cm longitudinally along the midline. The flexor tendons were not disturbed. The skin and subcutaneous tissue were then surgically closed with evenly placed interrupted 4-0 sutures. There were 5 sutures in each toe. The depth of each suture and the distance between the stitches were kept as identical as possible. The incised tendon sheath was not closed.

The 42 chickens were randomly assigned to the following 6 groups according to the timing of testing the resistance to tendon gliding. The timing of the toe harvest and the test performance was as follows: (1) 1 day after surgery, (2) 2 days after surgery, (3) 3 days after surgery, (4) 4 days after surgery, (5) 5 days after surgery, and (6) 7 days after surgery, with 14 toes at each time point. The toes were wrapped with sterile gauze and adhesive tape to protect the wounds, and were not immobilized. The dressing over the wound was only at the proximal part of the toes and the toes could move without restriction. To ensure that the dressing did not come off the toes, the tape was routed around the ankle and the dressing was checked daily after surgery. Two toes from which the dressing came off were excluded from analysis and were replaced with 2 toes of one supplemental animal.

The chickens in the nonsurgical control group did not have surgery, but the medial toes (total toes, 8) were tested for resistance to tendon motion in the same way as the toes in the surgical groups.

Grading of Tissue Edema

Both the severity and extent of digit edema were recently shown to contribute to resistance to tendon motion in an *in vitro* study[9] and are 2 variables associated with digit edema affecting resistance. Therefore, we used grading criteria to rate the edema in this study based on a recent report by Cao and Tang[9] in which the severity and extent of digital edema were classified into 3 categories. We used the criteria detailed in Table 1 to assess the degree of digit edema. The gross appearance of the digits was judged to show the following: (1) slight swelling, (2) moderate swelling, or (3) severe swelling (Fig. 1). The extent of the edema was as follows: (1) limited area, when the swelling is limited to the region of surgery or only around the wound over a short length; (2) extended area, when the swelling extends notably beyond the regions of surgery but not covering the entire digits; and (3) entire length of the

Table 1. Grading Criteria of Tissue Edema in the Digits

Scores	Grades	Features of Swelling in the Digits
Severity		
0	None	No swelling observed
1	Slight	Minimal or slight swelling, no notable changes in the depth of skin creases
2	Moderate	Obvious swelling of the digits, notable decreases in the depth of skin creases
3	Severe	Prominent swelling of the digits, increases in the digit diameter, and almost disappearance of skin creases
Extending area		
0	None	No swelling observed
1	Limited	Swelling limited to only around wounds or region of surgery
2	Extended	Swelling extending notably over the regions of surgery and exceeding one third of the digital length, but not to the entire digit
3	Extensive	Swelling extending to the entire length of the affected digits

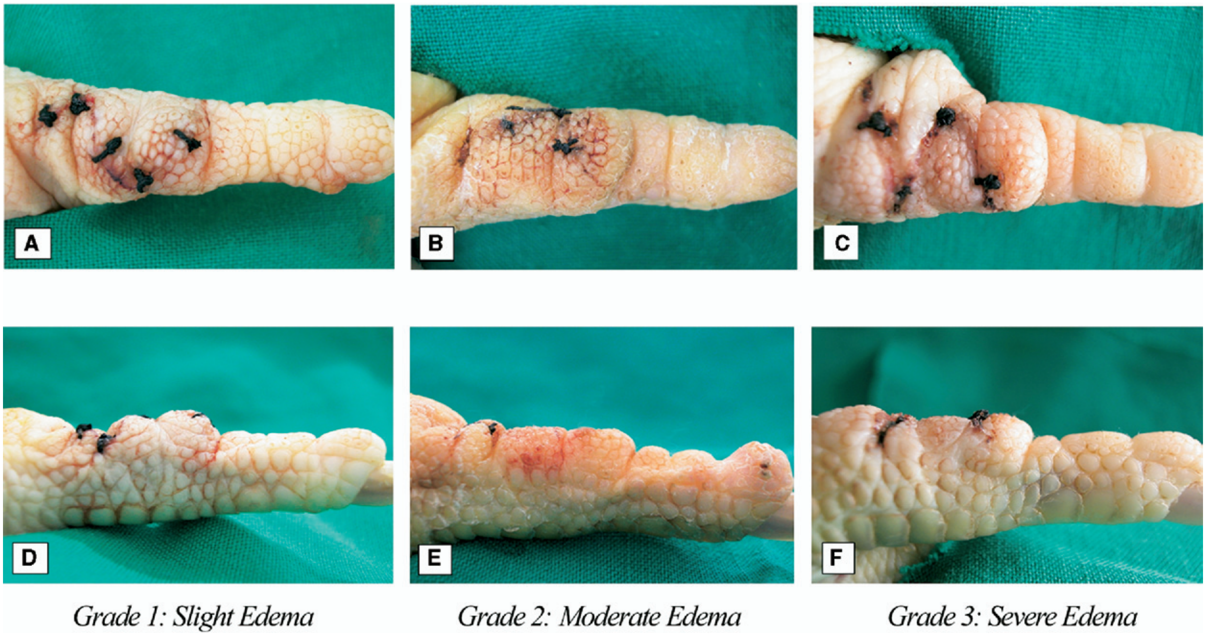

Figure 1. Severity of edema in the toes: (A–C) frontal view and (D–F) lateral view. (A and D) Slight edema, (B and E) moderate edema, and (C and F) severe edema. The difference between the slight and moderate edema is in the depth of skin creases and the general appearance of the swelling status; the severe edema is graded when prominent swelling together with an obvious increase in the diameter of the digit is noted.

digit, when the swelling is over the entire length of the affected digits. An incremental point score of tissue edema was given to each toe, combining scores of severity and those of extension; the total edema scores for individual toes were used to compare the changes in tissue edema quantitatively among the groups (Table 1).

We assessed the interrater and intrarater reliability of the grading criteria by enrolling 4 surgeons between 4 and 15 years of experience treating hand patients to grade postoperative edematous toes. For the assessment of intrarater reliability there was a 20-day interval between the 2 assessments for all raters, and raters used both frontal and lateral photographs of the edematous toes for assessments. The criteria had good to excellent interrater and intrarater reliability. The mean κ coefficient for the interrater reliability of these raters against the principle rater in this study was 0.61, and the κ coefficient for intrarater reliability was 0.82.

Resistance to Tendon Motion

Force and energy required to move the tendon. The toes were securely mounted to a board by transfixing the leg and metatarsal bones to the board with K-wires. The board was attached to the lower clamp of a materials testing machine (Model 4411; Instron Corp., Canton, MA) with a load cell of 500 N. The metatarsal bone was mounted with 2 K-wires with the toe tip pointing down, but the PIP, DIP, and distal DIP joints were not restricted. The toes were fully extended with a 15-g counterweight added to the tip of the toes. The flexor digitorum profundus (FDP) tendon was identified by its role in flexion of the distal DIP joint after a light pull proximally. The proximal end of the FDP tendon was connected to the upper clamp of the testing machine. A preload of 0.1 N was added to take away the slack in the tendon. The overhead cross-bar secured to the upper clamp was connected to a force transducer and advanced at a speed of 25 mm/min.[9,13] The load and displacement were continuously recorded with a testing software program (Series IX software; Instron Corp.) until a constant FDP tendon excursion (18 mm) was reached. Before the test, we confirmed that an excursion of 18 mm would enable the medial toes to flex completely. The end point of force and energy required to move the tendon were recorded. Eight toes from each surgical group were tested. Work is the area under the load-displacement curve, and the value was displayed on the monitor immediately after each test. The data obtained from the first run of the tendon were used for analysis.[10,11]

Force and energy after repetitive digital motion. In the remaining 6 toes from each group we cyclically loaded the toes for 10 cycles with 18 mm of consistent FDP tendon excursion. The toes were mounted and loaded as described previously. Cyclic loading of the tendons and repeated measurement of the force and energy were performed to observe the difference between the end-time force and energy recorded during the first cycle and the force and energy at later cycles after repetitive digital motion. After each run, the overhead cross-bar of the testing machine was returned to the starting position to release the tension on the tendon. We observed that all of the toes could return to full extension after the release of the load on the FDP tendon without application of loads in extensors or the toe tip because these toes had not been subjected to immobilization after surgery and no joint stiffness was present. By simultaneously displaying load-displacement curves of 10 test cycles obtained from each tendon in one plot, we observed how many cycles of toe motion could produce consistent load-displacement curves in the subsequent runs. Thereafter, we calculated the percent decrease of the force and energy recorded at the cycle starting to show consistent load-displacement curves in contrast to those at the first cycle.

Data Analysis

The data of force on the tendon and work of flexion of the toes obtained during the first run from the mechanical test were analyzed statistically by 1-way repeated-measure analysis of variance. When analysis of variance indicated significant differences in these data, the 2-tailed Tukey test was used to determine the statistical difference in the data between the groups as a *post hoc* test. For the comparison of difference in the force and work before and after cyclic loading a 2-tailed paired *t* test was used. In all cases a p value of less than .05 was considered significant. Statistical power was calculated for each *post hoc* test. We desired a statistical power of 0.80 or greater to avoid a type II error (not detecting the true difference) and to ensure sufficient reliability for significant statistical differences.

Results

Force and Work Required to Move the Tendon

There was a gradual increase in the force of the FDP tendon from day 1 to day 5 after surgery. The force was the lowest at day 1, and greatest at days 5 and 7. Statistically, the force at days 1 to 3 was significantly smaller than that at day 4 ($p < .05$ and $< .01$, respectively). The force at day 4 was significantly smaller than that at days 5 and 7 ($p < .05$ for both). The force was not significantly different between the toes measured on days 5 and 7. The force measured at days 5 or 7 was 2- to 3-fold higher, respectively, than at days 1 to 3 (Table 2) (Fig. 2).

Similarly, the work required to flex the toes gradually increased from day 1 to days 5 and 7. The work measured at days 5 and 7 was about 2-fold higher than at days 1 and 2 (Table 2). The work was significantly smaller at days 1 to 3 than at days 4 to 7 ($p < .05$ and $< .001$) (Fig. 2).

The statistical power was between 0.80 and 0.95 for all comparisons, except that the power was 0.70 for the comparison of work of flexion obtained at days 3 and 4.

Edema of the Digits

Analysis of edema over time showed less severity at days 1 and 2, a peak at days 3 and 4, and a decrease at day 5 (Fig. 2). Changes in edema in subcutaneous tissue did not parallel the changes in the force and work in this period; however, the more severe edema corresponded to greater gliding force of the tendon and work of toe flexion at each of the initial 5 postoperative days.

Changes in Resistance After Repetitive Digital Motion

We found that the force and energy became consistent after the fifth cycle of repetitive loading and the force-displacement curves were almost identical in subsequent runs 6 to 10.

As shown in Figure 3, repetitive motion of the toes significantly decreased the resistance to tendon mo-

Table 2. Gliding Force (N) of the FDP Tendon and Work of Toe Flexion (J) After Surgery

	Days After Surgery					
Evaluations	**1**	**2**	**3**	**4**	**5**	**7**
Force	3.5 ± 2.2	4.6 ± 1.7	5.6 ± 1.6	8.1 ± 1.3*	10.8 ± 2.3*,†	10.5 ± 3.2*,†
Work	0.022 ± 0.008	0.025 ± 0.007	0.027 ± 0.007	0.039 ± 0.009*	0.044 ± 0.013*	0.041 ± 0.010*

Values are means ± SD. The gliding force was 2.6 ± 0.5 N and the work was 0.019 ± 0.003 J in the toes of the nonsurgical control.
*Significantly different from the values at days 1 to 3.
†Significantly different from the values at day 4.

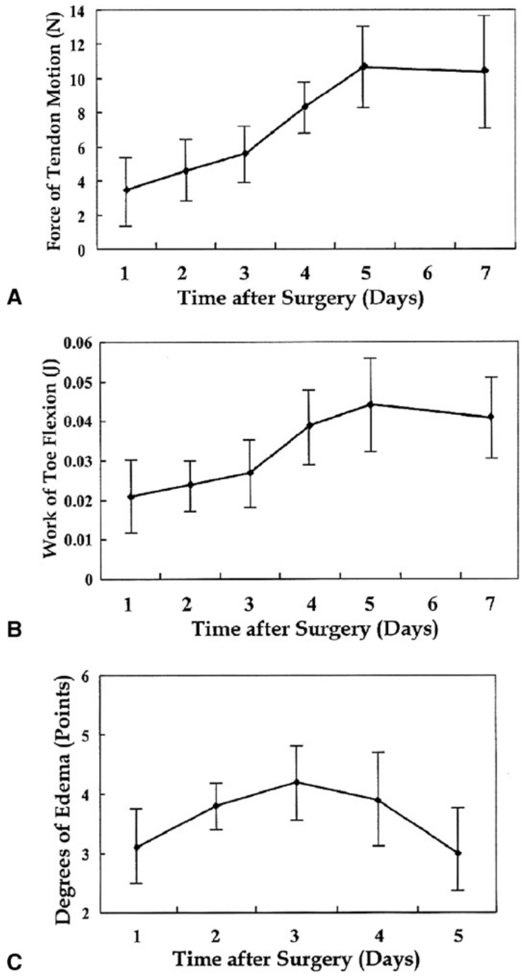

Figure 2. (A) Changes in force of the FDP tendon gliding, (B) work of toe flexion, and (C) degree of edema after surgery. The edema scores of individual toes were the mean combined scores of severity and those of the extent of edema. The lowest toe score was 2 because edema always presents around incisions after surgery.

tion at the early postoperative period. The force of tendon motion was decreased by 30% to 50% after 6 cycles of repetitive toe flexion compared with the first cycle. The work required to move the toes decreased by 30% to 35% after repetitive toe motion compared with the first cycle of toe flexion (Fig. 3). Statistically the decrease in either the force or work by simulated active flexion for 6 cycles was significant ($p < .001$, all comparisons), with a statistical power of 0.97 or 0.99.

Discussion

Problems associated with flexor tendon repairs are chiefly repair ruptures, digital stiffness, and adhesions.[3–5] Postoperative mobilization has been a credible method to prevent stiffness and adhesions, but it can cause repair rupture as noted in many reports.[5,15–20] Repairs can rupture as a result of the low strength of tendon repairs or an increase in resistance against active motion. Hence, resistance to tendon motion after surgery has recently become a subject of concern.[21–26] We hope to increase the strength of tendon repairs and minimize resistance during rehabilitation. Questions persist regarding exercise regimens, including the logical sequences of passive and active mobilization and the opportune time for commencement of exercise.

In this study, we recorded the degree of edema using original criteria. The severity of edema did not completely parallel changes in resistance over this 1-week period. Nevertheless, we observed on individual postoperative days the toes with severe edema corresponded to an increase in the force of tendon gliding and work of toe flexion. This finding indicates that the severity of edema can indicate changes in resistance to tendon motion. Although edema is clearly not the only factor in resistance to tendon gliding,[6–9] edema contributes considerably to resistance. Hence, judgment of severity of edema from gross appearance of the digits would provide clues to the resistance to tendon motion.

We noted that the resistance to tendon motion was relatively low in the first 3 days after surgery, after which it reached a relatively consistent higher level (days 4–7), although slight changes were observed. Our findings were in some aspects different from those of Zhao et al,[8] who noted a significant decrease in the force of canine tendon motion at 5 days and no decrease in the first 2 days after surgery. Canine flexor tendons, unlike those of human beings or chickens, lack a vincular system. Halikis et al[7] found that delaying mobilization until 5 days after surgery did not significantly reduce the peak work of flexion

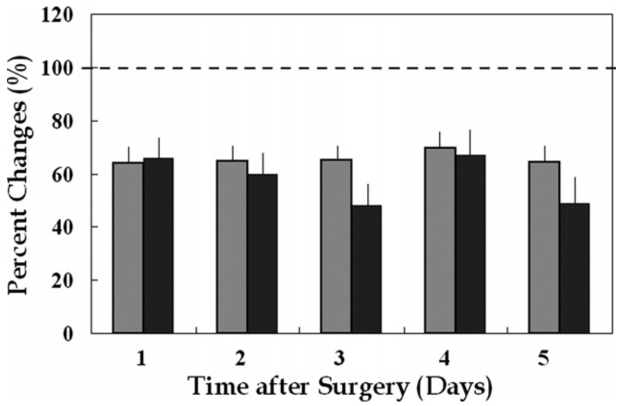

Figure 3. Changes of the force of tendon motion (gray bars) and work of toe flexion (dark bars) after the initial 6 cycles of repetitive toe flexion after surgery.

at 1 week in a chicken model, but delaying the period of mobilization until 3 days decreased the work of flexion at 1 week significantly. The exact reasons for the differences in these findings and ours are hard to determine but probably relate to differences in the animal models and because we investigated solely the resistance of the subcutaneous tissue and sheath.

Another result of this study is that repetitive loading of the tendon over a limited number of cycles (6 in this study) dramatically reduced the force of the tendon movement and work of flexion of the digits. The mechanism appears straightforward because continuous digital motion for a few cycles reduces stiffness of the digits and increases the viscoelasticity of the tendon. Given a gradual decrease in the force and work by 30% to 50% during the initial several cycles of simulated digital motion, we believe that gentle active motion for only several cycles would drastically reduce the resistance to subsequent tendon motion. Prior gentle mobilization, which reduces stiffness of the finger and may modify the viscoelasticity of the tendon, decreases overall resistance to tendon motion. Therefore, it likely increases the safety margin of subsequent aggressive or active motion exercise considerably.

The observation about earlier-mentioned merits of gentle motion of the digits before more aggressive motion appears to be valid, and may have potential importance in increasing the safety margin of rehabilitation protocols. The findings of resistance to tendon motion at the early postoperative period may help decide the optimum timing to start digital motion. We clearly see that the findings were from a model that had not incorporated tendon lacerations. The resistance to the uninjured tendon can be different from that to an injured tendon. Therefore, the number of cycles that a digit with or without tendon lacerations requires to reach a consistent and low level probably is different. The resistance to digital motion and the merits of prior gentle motion need to be validated further in a model with tendon injury and a motion regimen close to clinical settings.

Nevertheless, our findings may have relevance on several critical aspects of postoperative digital motion exercise. First, because of an increase in the resistance to the tendon in the first several days, motion is better started later to avoid overlapping an increase in the resistance; however, our data did not show significantly lower resistance at particular days. Rather, it appears that the opportune time to start the motion is from the fourth to seventh day after surgery, most appropriately starting on the fourth or fifth day. Apart from the evidence found in this study, 2 facts also support starting motion therapy in this time frame: (1) delaying the commencement of digital motion after surgery reduces the total number of motion episodes in the early healing stage, thus lessening the chance of rupture; and (2) motion during the early period appears unnecessary because adhesions do not form until later. According to our findings, starting digital motion in the initial days after surgery may increase the chance of repair ruptures because patients likely maintain nearly identical motion ranges and forces in the succeeding days, which see an increase in resistance. Starting motion on a later day would encounter a relatively consistent force, thus requiring fewer adjustments in the regimens; therefore, the exercise would be safer. Second, paying close attention to the severity of digital edema may be important in determining how we should apply finger motion regimens. In light of this study, we should be cautious in adopting aggressive exercise regimens in the presence of severe edema in the early postsurgical period. Third, finger motion for a number of cycles at the beginning of each episode of exercise would greatly reduce the resistance to subsequent movement. Gentle active or passive motion, targeted chiefly to eliminate finger stiffness, should therefore be applied before more aggressive active finger flexion. Gentle finger flexion serves as a warm-up for a more aggressive motion regimen.

Considering that the decrease in resistance in animal models may not exactly reflect the decrease in human beings and that the decrease in the force at 5 days as noted by Zhao et al[8] was actually small ($\approx$3 N), we believe that the most appropriate time for beginning motion is probably a period rather than a specific day. The opportune period likely is from day 4 to 7 after surgery, most probably on the fourth or fifth day, depending on the judgment of surgeons and therapists about tendon strength versus resistance, according to the morphologic appearance of edema, the extent of the injuries, and the strength of the repair techniques used. We further recommend that the degree of finger edema should be judged and recorded from gross appearance as an aid to determine the timing and aggressiveness of motion therapy because we see that the morphology of edema in the early postsurgical days corresponds to changes in the resistance to tendon motion.

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