Wrist and digital joint motion produce unique flexor tendon force and excursion in the canine forelimb

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Abstract

The force and excursion within the canine digital flexor tendons were measured during passive joint manipulations that simulate those used during rehabilitation after flexor tendon repair and during active muscle contraction, simulating the active rehabilitation protocol. Tendon force was measured using a small buckle placed upon the tendon while excursion was measured using a suture marker and video analysis method. Passive finger motion imposed with the wrist flexed resulted in dramatically lower tendon force (~5 N) compared to passive motion imposed with the wrist extended (~17 N). Lower excursions were seen at the level of the proximal interphalangeal joint with the wrist flexed (~1.5 mm) while high excursion was observed when the wrist was extended or when synergistic finger and wrist motion were imposed (~3.5 mm). Bivariate discriminant analysis of both force and excursion data revealed a natural clustering of the data into three general mechanical paradigms. With the wrist extended and with either one finger or four fingers manipulated, tendons experienced high loads of ~1500 g and high excursions of ~3.5 mm. In contrast, the same manipulations performed with the wrist flexed resulted in low tendon forces (~4–8 N) and low tendon excursion (~1.5 mm). Synergistic wrist and finger manipulation provided the third paradigm where tendon force was relatively low (~4–8 N) but excursion was as high as those seen in the groups which were manipulated with the wrist extended. Active muscle contraction produced a modest tendon excursion (~1 mm) and high or low tendon force with the wrist extended or flexed, respectively. These data provide the basis for experimentally testable hypotheses with regard to the factors that most significantly affect functional recovery after digital flexor tendon injury and define the normal mechanical operating characteristics of these tendons. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Wrist and digital joint motion; Tendon force; Tendon excursion

1. Introduction

Early controlled motion rehabilitation decreases adhesion formation after intrasynovial flexor tendon repair and increases joint range of motion, improves repair site strength, and enhances functional recovery (Feehan and Beauchene, 1990; Hitchcock et al., 1987; Strickland and Glogovac, 1980; Takai et al., 1991). Previous studies have provided detailed descriptions of the biomechanical, biochemical and morphological properties of repaired tendons treated with controlled motion, however, the mechanism by which mobilization facilitates the recovery of digital function is not completely understood. Whether excursion and load affect functional recovery separately but equally, whether they interact to facilitate recovery or whether they oppose one another has not been determined. Furthermore, the excursions borne by flexor tendons during joint mobilization such as those commonly advocated in rehabilitation have not been reported.

Active motion (i.e., joint motion powered by muscle contraction) after tendon repair was advocated recently as a means of increasing the in vivo tendon force and enhancing the repair process. Small et al. (1989) reported 77% good to excellent results in a series of 114 patients treated with controlled active rehabilitation, and noted a reduced rate of revision surgeries (tenolysis). However,
these authors also reported a 10% repair site rupture rate, illustrating the need to identify safe limits for forces applied during active rehabilitation. To address this issue, Schuind et al. (1992) measured the in vivo flexor tendon force corresponding to different active and passive wrist and finger motions in patients who were undergoing carpal tunnel surgery. They reported average flexor digitorum profundus (FDP) forces values of approximately 1 N for passive finger flexion, 3 N for passive wrist extension, 20 N for active finger flexion and 40 N for active grasp.

In the canine model, the tensile force borne by FDP tendons during passive wrist and digit manipulation was found to depend primarily on wrist position and less on digital position (Lieber et al., 1996). The highest tendon forces were measured when the digits were manipulated with the wrist extended. The force generated by the FDP muscles was also measured directly and shown to be, under certain conditions, quite close to the passive forces achieved with the wrist extended. These data, which indicate that passive joint manipulation results in tendon forces that are similar to those generated during active muscle contraction, raise the concern that repair site rupture from controlled motion could result depending on the methods used. However, this previous study did not report the excursions corresponding to the various joint configurations. Tendon excursion may be as important or even more important than passive load in achieving functional recovery after repair. Thus, the purpose of this study was to measure tendon force and tendon excursion simultaneously in the canine flexor tendons during passive joint manipulations and during active muscle contraction in order to simulate commonly utilized controlled active and passive rehabilitation protocols. A brief version of this work has been presented (Lieber et al., 1998).

2. Methods

The experimental model used for this study was the flexor tendon of adult mongrel dogs (5 forelimbs from 4 dogs). This model has been used extensively in our laboratory for studies of tendon microcirculation, tendon healing, and tendon biomechanics. Animals were administered a preanesthetic dose of Ketamine/xylazine/rompum cocktail (5, 50, and 1 mg kg⁻¹ body mass, respectively) and maintained on isoflurane anesthesia. The FDP tendon of the medial digit was isolated through a mid-lateral incision just proximal to the A-2 pulley along the surface of the metacarpal shaft (Fig. 1). A small Z-shaped force transducer was placed on the tendon at the level of the midmetacarpal for force measurement as previously described (Lieber et al., 1996). Care was taken to insure that the transducer itself was not limited by adjacent structures which could cause artifactually high forces. India ink dye lines were placed on the edges of the A2 pulley and 3-0 nylon sutures were placed in the tendon substance proximal and distal to the pulleys to permit excursion measurements (Fig. 1). A special loop suture was created with the knot on the inferior tendon surface such that the nylon suture created a very sharp line that could be easily recorded on videotape. Care was taken to place the suture so that joint rotation did not result in the suture marker passing beneath the sheath or out of the field of view where it could not be tracked.

To record tendon excursion, a CCD video camera was placed perpendicular to the long axis of the tendon and oriented in two planes such that, during finger and wrist joint rotation, both the dye lines and sutures stayed in focus. Since the lens setting used was approximately F1.8 and the calculated depth of field approximately 0.5 mm, under these conditions, the vertical movement of the markers was less than 0.25 mm. Since the overall excursions measured were in the range 3–8 mm, no correction for parallax was made.

The experimental design consisted of wrist and finger manipulation over their entire range of motion in one of five configurations; Single finger flexion-extension with the wrist fully flexed (Group 1F), single finger flexion-extension with the wrist fully extended (Group 1E), four finger flexion-extension with the wrist fully flexed (Group 4F), four finger flexion-extension with the wrist fully extended (Group 4E), and synergistic motion where wrist extension and finger flexion were performed alternately with wrist flexion and finger extension (group SYN). Full wrist extension was ~15° while full flexion was ~80°. Digits could be flexed at the interphalangeal joints to ~75° and the DIP could be hyperextended by ~15°. All
motions were performed by manual manipulation for approximately 70 s during which force data from 3 to 7 manipulation cycles were acquired by computer at 150 Hz and excursion was recorded at 30 Hz on Hi-8 8 mm format videotape. Force and excursion data were synchronized using a 10 V output pulse from the computer placed on the video sound track.

To simulate the effects of an active rehabilitation protocol (Silfverskiold and May, 1995), tendon force and excursion were measured during stimulation of the digital flexor muscle near the medial epicondyle. A pair of bipolar activating electrodes were placed in the muscle approximately 1.5 cm distal to the medial epicondyle and stimulation was induced using a stimulator (Grass Model S44, Grass Instruments, Quincy, MA) with a maximum current output of 250 mA and an output impedance of 250 Ω. Muscles were stimulated over the range 10–60 Hz and tendon force measured with the wrist in either the flexed or extended position to determine the maximal force generating capacity of these muscles. Previous studies had demonstrated maximum active muscle force was achieved with the wrist in full extension and that force decreased linearly as the wrist was fully flexed. Thus, the canine FDP operates on the ascending limb of its length-tension curve in this configuration (Lieber et al., 1996). Because the digital and wrist tendons on the palmar aspect of the distal forearm were exposed, it was possible to place electrodes such that only FDP activation occurred. In the case where other muscles were seen activated (typically the flexor carpi ulnaris), stimulating electrodes were repositioned to correct the problem. Electrical stimulation was performed with the joint in the 4F and 4E positions.

To measure tendon excursion, the linear distance between the proximal tendon suture and the proximal edge of the A-1 pulley was measured throughout the digital manipulation cycle. For each joint manipulation cycle, the maximum (d<sub>max</sub>) and minimum (d<sub>min</sub>) straight-line distance was recorded and the overall change in distance (Δd) was calculated as Δd = d<sub>max</sub> - d<sub>min</sub>. Within a sequence of 3–7 cycles, the maximum Δd of all cycles was used to represent that joint configuration for that limb. Variations in Δd occurred not only due to slight variations in the natural tendon excursion under identical conditions, but also due to the slight variability in the kinematics of joint motion that was imposed manually. Repeated measures of Δd over the 3–7 joint manipulation cycles trials yielded a sample standard deviation (σ) of about 0.5 mm.

Distances were measured manually on a video monitor that was overlaid with an acetate sheet. Suture markers were tracked as the videotape was advanced on a frame-by-frame basis. Magnification of the camera, video and monitor configuration was 5.1 and measurement resolution was 1.0 mm corresponding to a real distance of approximately 0.2 mm.

Error associated with the straight line assumption for distance measurement between the suture marker and pulley edge was determined by digitizing complete video records selected randomly and measuring actual curvilinear distance along the tendon length on a frame by frame basis. Differences between the values measured using this method and linear measurement method were less than 10%, and only the linear measurement data are reported.

To determine the strain experienced by the FDP tendons during the in vivo joint manipulation, the same tendons on which force and excursion data were obtained were excised after euthanizing the animal to permit testing of material properties under the same loads measured. Briefly, tendons were dissected free of surrounding musculature with care taken to keep the specimens moist by bathing it in saline at all times (Loren and Lieber, 1995). Using elastin stain, transverse dye lines were applied at a 10 mm gauge length after cautious removal of the peritenon. The tendon was placed in a 37°C saline bath, and clamped to the arm of a dual-mode serve-motor (Model 310B, Cambridge Technology, Inc., Watertown, MA) permitting controlled loading. The free end of tendon was secured to a stationary clamp yielding about 30 mm of exposed tendons between clamps.

A digital function generator (Model 3314A, Hewlett-Packard Co., Everett, WA) was programmed to drive the motor in 5 linear load-unload cycles to the peak load measured during joint manipulation, which occurred in the 4E configuration for all specimens tested. To minimize strain rate effects, load was imparted over a 30 s interval (0.017 Hz) and released over a consecutive period, with actual strain rates ranging from 0.05 to 0.14%/s. Simultaneous force-time records were obtained at 0.1 s intervals via the servo-motor interfaced with a Macintosh IIx computer (Apple Computer, Inc., Cupertino, CA) using SuperScope software (version 1.0, GW Instruments, Inc., Somerville, MA). The experiment was video-recorded for subsequent strain analysis. The fourth force-deformation cycle was utilized for strain analysis using a video dimension analyzer (VDA; Model 303, PIM, Inc., San Diego, CA; Woo et al., 1983). The VDA signal was amplified by a factor of 100 and low-pass filtered at 10 Hz (Universal Amplifier 13-4615-58, Gould, Inc., Cleveland, OH) prior to computer acquisition. Each specimen was strain-tracked 3 times from parallel regions of the tendon specimen with records averaged over time. From corresponding points on the load–time relationship and strain–time relationship, the load–strain curve was constructed (Woo et al., 1983).

Statistical comparison of peak force and peak excursion between experimental groups was performed by one-way analysis of variance (ANOVA) with repeated measures. Significant ANOVA results were followed by
post hoc comparison between means using Fischer’s PLSD test (Statview 4.5, Abacus Concepts, Inc., Berkeley, CA). Excursions were tested for significant difference from zero using a one-sampled t-test. To determine whether the five passive tension experimental groups represented unique biomechanical paradigms, discriminant analysis was used. In this case, both excursion and force were implemented in a bivariate analysis whereby F-to-Enter = 4.000 and F-to-Remove = 3.998 were used to create the discriminating function. All 20 experimental data records were then reclassified post hoc to provide objective grouping information. Discriminant analysis could not be applied to the active stimulation groups since their data were not independent of those reported for passive joint manipulation. Data were screened for normality and skew to justify the use of parametric statistics. Significance level (α) was chosen as 0.05 and statistical power (1 − β) was calculated as 45% using standard equations (Sokal and Rohlf, 1981) when significance level exceeded 0.05 (see Results). Data are presented in the text as mean ± standard error of the mean unless otherwise noted.

3. Results

Passive tendon force varied significantly between experimental groups (p < 0.001) similar to that reported previously (Lieber et al., 1996). Finger motion imposed with the wrist flexed resulted in dramatically lower tendon load compared to motion imposed with the wrist extended (Fig. 2A). The use of one vs, all four digits had a negligible effect. Post hoc comparison between means revealed that, with regard to force generation, groups 1E and 4E did not differ from each other (p > 0.3), but were both significantly higher than groups 1F, 4F and SYN (p < 0.001). Groups 1F, 4F and SYN were not significantly different from each other (p > 0.4). Thus, high passive forces were achieved with the wrist extended and low passive forces achieved with the wrist flexed or with synergistic wrist and finger motion.

Repeated measures of marker position over 10 trials yielded a sample standard deviation of 0.23 mm while repeated measurement of Δd during a given joint manipulation maneuver yielded a sample standard deviation of 0.41 mm. Passive tendon excursion measurements also varied significantly between groups (p < 0.005, Fig. 2B). High excursions were observed when either the 1E, 4E, or SYN high force joint manipulations were performed, while lower excursions were seen for conditions 1F or 4F. A significant difference was observed between each of the three high excursion groups (1E, 4E and SYN) and each of the two low excursion groups (1F and 4F, p < 0.01 for each of the 6 paired comparisons). The absolute excursion in the high excursion groups (~3.5 mm) was over twice that in the low excursion groups (~1.5 mm). In all cases, the excursions observed were significantly different from zero (p < 0.005).

Bivariate analysis of both force and excursion data revealed a natural clustering of the five experimental groups into three general mechanical paradigms (Fig. 3). With the wrist extended and with either one finger or four fingers manipulated (Groups 1E and 4E), tendons experienced high loads of ~15 N and high excursions of ~3.5 mm. In contrast, the same manipulations performed with the wrist flexed (Groups 1F and 4F) resulted in both low tendon forces (4–8 N) and low tendon excursions of ~1.5 mm. Synergistic wrist and finger manipulation (SYN) provided the third paradigm where tendon force was relatively low (~4 N) but excursion was as high as those seen in the groups which were manipulated with the wrist extended.

When data were analyzed by discriminant analysis using F-to-Enter = 4.000 and F-to-Remove of 3.998, the two discriminating parameters, Δd and force were able to correctly classify all 20 cases into the correct mechanical paradigm, but it was not possible to resolve the difference between data from groups 1F and 4F or between groups 1E and 4E. All cases in group SYN were correctly classified. These data provide objective justification for considering our data as representing three general mechanical paradigms.

Electrical stimulation of the FDP muscle mass produced very low tendon loads with the wrist flexed (~2 N,
Excursion induced by FDP muscle activation did not vary significantly between groups ($p > 0.5$; Fig. 3). Interestingly, the excursions were relatively low ($\sim 1$ mm) under the conditions of either a flexed or extended wrist but for different reasons. Under condition 4F, the low force produced by the muscle and its inability to shorten could barely overcome the passive friction within the A-2 pulley resulting in an excursion of $1.18 \pm 0.41$ mm. However, with the wrist extended (group 4E), in spite of the fact that the FDP muscle produced over 30 N of force, because of the high passive tension in the muscle (15 N, Lieber et al., 1996), the tendon was already taught and unable to move appreciably ($0.78 \pm 0.48$ mm). Thus, under all of the conditions explored in this study, muscle activation created only a small amount of additional excursion, although this small amount was significantly different from zero ($p < 0.01$). It should be noted that the statistical power of the comparison between *d* measured during active stimulation measured with the wrist in the flexed and extended positions was only about 50%.

Tendon strain was highly nonlinear as each tendon specimen was loaded to $P_0$, the maximum tetanic tension of each respective muscle. These tensions ranged from 12.9 to 27.9 N which was believed to represent the size differences between animals (Table 1). In spite of these relatively large differences between muscles for $P_0$, the load strain relationships were relatively consistent and well-fit by an equation of the form

$$\sigma = a \cdot 10^{be},$$

(1)

where $\sigma$ represents tendon stress (expressed as a percentage of the maximum muscle stress), $b$ represents tendon strain and $a$ and $b$ represent the curve fit parameters. All correlation coefficients exceed 0.9 indicating an excellent fit. Strain at $P_0$ was calculated for each tendon by solving each tendon’s Eq. (1) for $\varepsilon$ when $\sigma = 100$. The mean tendon strain was $3.3 \pm 0.2$% (Fig. 4).

### Table 1

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<th>Specimen #</th>
<th>Dog mass (kg)</th>
<th>$P_0$ measured (N)</th>
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<th>$b$ Value</th>
<th>$r^2$</th>
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Note: Values represent the curve fit of tendon mechanical properties loaded to the maximum tetanic tension of the associated FDP muscle.

**4. Discussion**

This study demonstrated that joint manipulation, such as that commonly advocated for rehabilitation of flexor tendon injury, has a profound effect on the force borne by the tendons as well as their excursion. Using discriminant analysis, a multivariate method for objectively classifying data, we demonstrated that the five joint manipulation protocols studied result in three distinct mechanical
paradigms: high force–high excursion, low force–low excursion, and low force–high excursion (Fig. 3). In the canine system studied here, the number of digits manipulated had almost no effect on these mechanical parameters.

It has not been determined whether or not tendon healing and ultimate functional recovery are more dependent upon tendon force or tendon excursion or whether there is an interaction between the two. Based on the current data, it might be argued that, if high loads were to be avoided during early mobilization, rehabilitation motions should be performed without the wrist and fingers extended. However, the lower loads achieved under these conditions may not produce the tendon sliding which is believed to be beneficial to the recovery process. It may be that repair site healing depends as much on high excursion as it does on the applied load to the repair site. The current data provide the basis for an experimentally testable hypothesis with regard to the factors that most significantly affect functional recovery after digital flexor tendon injury. We provide guidelines for experimental manipulation of force and excursion independently in an in vivo model that will allow the testing of their relative importance. Ideally, a 2 × 2 ANOVA model would be implemented to measure tendon healing in the presence of high force–high excursion, low force–low excursion, low force–high excursion and high force–low excursion protocols. Unfortunately, no combination of passive wrist and finger motion yield the high force–low excursion combination. One could implement the high force–low excursion group using electrical stimulation with the wrist in either the flexed or extended position. The only difference between these two treatments would be the passive force which would be high (~15N) in the case of the extended wrist. The excursion in both cases would be on the order of 1 mm. Thus, if one desired a rehabilitation strategy that involved high tendon excursion but low tendon force, clearly the SYN group would be preferred. If, on the other hand, both high tendon excursions and high tendon loads were desired, either Group 1E or 4E could be used. Finally, if both low tendon force and low tendon excursion were desired, either Group 1F or 4F could be used. Which, if any of these protocols produces the best results remains to be determined.

Deliberate modulation of passive and active FDP muscle force with joint manipulation has practical rehabilitation consequences — force can be altered directly and linearly by simply varying wrist joint angle. Given that only ~ 2.5 N of force is generated by the FDP with the wrist flexed (+75°) and over 30 N is generated with the wrist extended (~35°), FDP muscle force increases by about 0.3 N degree−1 or ~1%P0 degree−1 wrist extension as the muscle moves up the ascending limb of the length-tension curve. If the 1F/4F tendon forces observed were lower than desired but the 1E/4E tendon forces were excessive, the wrist could simply be placed in an intermediate position that could provide any desired intermediate force. This information could be combined with the values for the ultimate tensile properties of the flexor tendon repair site to recommend progressively extended wrist joint angles and increased FDP tendon force during the rehabilitation protocol as the tendon was able to bear the higher loads. Clearly, these data provide important basic science information that can be applied ultimately to create novel strategies for rehabilitation of flexor tendons.

Finally, a number of limitations of this study should be detailed. The most important limitation is that only linear distances between the tendon marker and sheath were measured. As mentioned in Methods, direct comparison between curvilinear and linear measurements resulted in underestimation of excursion values by about 10%. This value is only important to the extent that it differs between the experiment groups studied. We observed no difference between groups in the tendency for the tendon to ‘buckle’ during joint manipulation which would systematically bias our results. Next, we considered the tendon as a rigid body acting along pulleys. However, marker movement could result not only from tendon translation, but from material strain of the tendon itself. Under conditions of maximum muscle activation (achieving similar forces as the 1E and 4E groups), average tendon strain was 3.3% suggesting that, of the total 3 mm excursion reported, approximately 0.1 mm could have been due to tendon strain rather than true tendon gliding which does not affect the conclusions of this study. Finally, the relatively small sample size resulted in low statistical power comparing the tendon excursion during active stimulation. In this case, power calculations reveal that a sample size of 11 would have resulted in a significant difference between flexed and extended positions of this magnitude (0.4 mm).

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