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Does Loading Velocity Affect Failure Strength after Tendon Repair?

Manoj Parimi, B.S., Chunfeng Zhao, M.D., Andrew R. Thoreson, M.S., Kai-Nan An, Ph.D., and Peter C. Amadio, M.D.

Biomechanics Laboratory, Division of Orthopedic Research, Mayo Clinic, Rochester, MN

Abstract

Tensile testing of repaired tendons has been used to assess the efficacy of repair techniques. However, individuals flex and extend fingers at rates higher than those typically used for testing. This study characterized the effect of loading rate on the failure strength of repaired canine flexor tendons. Thirty six canine flexor digitorum profundus tendons were lacerated, repaired, and tested at three displacement rates: 0.33 mm/s; 84 mm/s; and 590 mm/s. Peak force and stiffness of the repairs were evaluated. Peak force was significantly greater ($p < 0.05$) for tendons distracted at 590 mm/s than at 0.33 mm/s. Crosshead stiffness was significantly greater for tendons distracted at 590 mm/s than at either 84 mm/s or 0.33 mm/s. The predominant failure mode was core suture knot untying. Distracting tendons at slow loading rates provides a conservative assessment of tendon repair strength. Additionally, an estimate of the failure load of this repair for different clinical events has been identified.

Keywords

Tendon Repair; Rate Dependence; Suture; Mechanical Testing; Kinematics

INTRODUCTION

Tendons are viscoelastic structures (Nordin and Frankel, 2001); tendon repair strength is also likely rate dependent. Tendon repairs often fail as a result of a sudden motion (Deslandes et al., 2008). However, most studies investigating tendon repair apply relatively slow loading rates, often in the range of 0.33 mm/s (Liu et al., 2011; Momose et al., 2001). In contrast, the flexor pollicis longus velocity in healthy individuals ranges between 80 mm/s and 180 mm/s (Cigali et al., 1996). Rates during tendon injuries associated with sudden falls may be as high as 590 mm/sec (Troy and Grabiner, 2007).

Many studies have described the strength of different suture materials and techniques. None, that we are aware of, have considered the circumstances in which such repairs fail: an

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Corresponding Author: Peter C. Amadio, M.D., Mayo Clinic, Orthopedic Biomechanics Laboratory, 200 First Street SW, Rochester, MN 55905, Tel: 507-538-1717 Fax: 507-284-5392, pamadio@mayo.edu.

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CONFLICT OF INTEREST

The authors confirm that there is no potential conflict of interest including employment, consultancies, stock ownership, honoraria, and paid expert testimony, and patent applications influencing this work.

acceleration-deceleration mechanism has been reported in up to 90% of cases of Achilles tendon rupture (Harris et al., 1999; Soldatis et al., 1997). The purpose of this study was to characterize the loading rate effect on a repaired canine flexor digitorum profundus (FDP) tendon. We hypothesized that different velocities would result in significantly different mechanical properties when tested in an established tendon repair model.

MATERIALS AND METHODS

Specimen Preparation

Thirty-six FDP tendons from 5 mixed breed dogs (20 to 25 kg) were tested. Canines are commonly used to study the biological effects of tendon injuries and treatment (Tanaka et al., 2005). Tendons of the 2nd through 5th digits of each hindpaw were harvested from dogs sacrificed for other, IACUC-approved studies. FDP tendons were isolated and transected at the proximal interphalangeal joint level. All tendons were repaired with a modified Kessler technique with 3/0 Ethibond suture (Ethicon Somerville, NJ) and a 6/0 Prolene (Ethicon Somerville, NJ) running suture. Each repair had a 5-mm purchase on either side of the laceration with locking loops. A peripheral 6-0 polypropylene (Prolene, Ethicon, New Brunswick, NJ) finishing stitch was also used. All repairs were performed by the same individual. The 2nd through 5th digit FDP tendons were equally divided among the three groups.

Testing Device and Velocity Effect

Repaired tendons were clamped into a servo-hydraulic testing machine (MTS Systems, Inc., Eden Prairie, MN). To minimize inertial vibrations that would distort data, a clamp of minimal mass (33 g) was used to connect tendons to the load cell. A 10-cm diameter foam pad was placed underneath the load cell to damp additional vibrations (Figure 1a). A differential variable reluctance transducer (DVRT) (MicroStrain, Burlington, VT) was fixed to either side of the laceration to measure gap formation. A conditioning pre-load was applied by distracting tendons at 20 mm/min to a load of 2 N, followed by a sinusoidal load profile with a 0.25-mm amplitude and 0.5-Hz frequency for a total of 10 cycles (Baumfeld et al., 2010; Rhee et al., 2011). Tendons were distracted to failure at one of three randomly assigned displacement rates: 0.33 mm/s, 84 mm/s, and 590 mm/s. Tensile force, crosshead displacement, and DVRT displacement were recorded at a sample rate of 1024 Hz. Ultimate failure load and stiffness were determined. Stiffness was calculated from the slope of the force vs. crosshead displacement curve. Failure mode was recorded.

Knot Preparation and Testing

To evaluate the role of the knot alone and how it is influenced by loading rate, 24 square knot loops were prepared and tested to failure using the same three rates (Figure 1b). Tensile force was recorded at a sample rate of 1024 Hz. Failure mode was recorded.

STATISTICAL ANALYSIS

Sample size was determined through a power analysis using data from a previous study investigating strength of different suture techniques (Tanaka et al., 2004). Standard deviation was expected to be as much as 25% of the mean peak force. 12 specimen per group were required to achieve 80% power to detect a 30% difference between groups, the threshold selected for clinical significance.

Data, reported as mean±SD, were analyzed with one-way analysis of variance followed by the Tukey-Kramer *post hoc* test if significant differences were identified. A level of $p < 0.05$ was considered to be statistically significant.

RESULTS

Peak force was significantly greater ($p=0.012$) for the tendons distracted at 590 mm/s than those distracted at 0.33 mm/s (Figure 2). The DVRT was intended to measure gap formation at the repair site to calculate local repair stiffness. However, at the two highest loading rates, stiffness during initial moments of testing approached infinite values, likely resulting from failure to align the DVRT perfectly parallel to the tendon prior to testing – the transducer rotated rather than permitting displacement of the piston. Crosshead stiffness was used as a more reliable measure of repair site stiffness. Stiffness was significantly greater for tendons distracted at 590 mm/s than those distracted at either 84 mm/s ($p=0.0019$) or 0.33 mm/s ($p<0.001$) (Figure 2).

Three different failure modes were observed: core suture breakage, suture pullout, and knot untying (Figure 3). The 0.33 mm/s group exhibited the greatest variety of failure modes (Figure 4).

Peak forces observed in the knotted loop testing (27.6 ± 8.0 , 33.3 ± 8.8 , and 25.7 ± 13.4 N for the 0.33, 83, and 590 mm/s groups, respectively) were not significantly different between the three velocities ($p=0.322$). Two different modes of failure were observed: core suture breakage and knot untying.

DISCUSSION

In this study, higher loading rates increased both stiffness and peak force, in some cases significantly. Wu looked at the viscoelastic properties of intact flexor tendons and showed that higher velocities resulted in both increased stiffness and ultimate stress for strain rates between 0.003 s^{-1} and 0.1 s^{-1} (Wu, 2006). Our data is consistent with this observation and establishes this same pattern at higher velocities ($>0.15\text{ s}^{-1}$).

Significant differences were not observed between the mean failure force or stiffness between the 84 mm/sec and 590 mm/sec groups. This suggests that once a velocity threshold is reached, failure occurs in a similar fashion. In both cases, failure most often occurred by knot unraveling, also supporting the idea that failure becomes similar beyond a threshold.

The predominant failure mode across all three groups was the untying of the core suture square knot of the modified Kessler repair. The security and holding strength of the square knot have long been discussed; such knots frequently fail by unraveling rather than breakage, as observed here (Fong et al., 2008; Herrmann, 1971; Howes, 1933; Muffly et al., 2010; Taylor, 1938). Knot security is especially important in flexor tendon repair where the repaired tendons bear high tensile forces post-operation. Knot unraveling, accounting for the majority of failures in testing at 84 mm/sec (normal physiologic motion) and 590 mm/sec (sudden fall), raises questions about the security of knots when distracted at different loading rates and should be investigated further.

Knot testing data clearly showed there was no difference among the three different groups. As a result, we are able to safely conclude that the different velocities have no effect on the failure strengths of square knots alone.

Results show that failure strength in this tendon repair model is significantly greater with an action simulating a sudden fall (590 mm/sec) than with actions that are slower than normal physiologic motion (0.33 mm/sec). However, this observation is tempered by some study limitations.

One limitation of this study is that only one repair design was evaluated. The modified Kessler technique was evaluated because it is commonly used clinically and experimentally. Although recognizing that suture materials and repair designs vary in stiffness, it was assumed that rate would most affect the tendon, not the stiffness of the suture.

Another limitation is that tendons were tested in a linear distraction model. Clinically, tendons follow a curved path through the pulley system. Testing in a more anatomic model may yield different results. One study has demonstrated that increased angle of curvature decreased the strength in the tendons (Tang et al., 2001). This study looked at one of many different modes by which a repaired tendon can fail.

Use of the DVRT intended to measure gap formation may have had an effect on the failure strength, and our inability to collect reliable data at higher rates may mask effects of rate on local repair site stiffness. The device was inserted a few millimeters beyond the suture site outside of the repair. Although the tendon may have been damaged, it likely had very little effect on the strength of the repair.

Finally, since a single individual repaired all tendons in this study, we cannot assess inter/intra operator influences on the results.

In summary, we found that strength of repaired tendons is rate dependent, with higher strain rates resulting in higher breaking strength. Thus, conventional failure testing of tendon repairs at 0.33 mm/s gives a conservative value of strength, adding a margin of safety to reported values. Additional studies should be performed to determine if these findings are reproduced with more physiologic (i.e., curved) models, and using different repair designs.

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Figure 1. Mechanical test set-up for a) repaired tendon testing with DVRT to measure repair site displacement and b) knotted loop test. Both test set-ups require vibration damping.

Figure 2. Mean failure force and stiffness at three loading rates (*, ** indicates significant difference for force and stiffness groups, respectively, $p < 0.05$; whiskers indicate standard deviation).

Figure 3. Primary failure modes observed: A) core suture knot untied; B) core suture pullout; C) core suture breakage.

Figure 4.

Frequency of failure mode (suture pullout, knot untied, core suture breakage) for the three velocity groups.