SCIENTIFIC ARTICLE

Gap Formation During Cyclic Testing of Flexor Tendon Repair

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Purpose Substantial gap formation of a repaired finger flexor tendon is assumed to be harmful for tendon healing. The purpose of this study was to investigate the relationship between gap formation and the failure of the repair during cyclic loading.

Methods Thirty-five porcine flexor tendons were repaired and tested cyclically using variable forces until failure or a maximum of 500 cycles. Depending on the biomechanical behavior during cyclic testing, specimens were divided into 3 groups: Sustained (no failure), Fatigued (failure after 50 cycles), and Disrupted (failure before 50 cycles). The relationships between the gap formations, time-extension curves, and group assignments of the samples were investigated.

Results The time-extension curves of the Fatigued specimens showed a sudden onset of repair elongation—a fatigue point—which preluded the subsequent failure of the repair. This point coincides with the start of plastic deformation and, thereafter, cumulative injury of the repair consistently led to failure of the repair during subsequent cycles. None of the sustained repairs showed a fatigue point or substantial gapping during loading.

Conclusions We conclude that the emergence of a fatigue point and subsequent gap formation during loading will lead to failure of the repair if loading is continued.

Clinical relevance The results of this experimental study imply that an inadequate flexor tendon repair that is susceptible to gap formation is under risk of failure. *(J Hand Surg Am. 2017;■(■):1.e1-e8. Copyright © 2017 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Hand surgery, finger, flexor digitorum profundus, biomechanical testing.

Online Exclusive

GAP FORMATION BETWEEN THE TENDON ends has been shown to result in harmful effects on recovery after flexor tendon repair surgery. Gapping leads to increased gliding resistance[1] and predisposes to adhesion formation, subsequent need for tenolysis,[2] and decreased mechanical strength.[3]

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Gapping loads (eg, 1 or 2 mm) and ultimate load are among the most often reported parameters in static linear testing. These values are used to determine the biomechanical properties and strength of a tendon repair and to compare different techniques. In static linear testing, early gapping has been found to correlate with the onset of the disruption of the repair, and under the ultimate load, the tendon ends may be several millimeters apart from each other.[4] Therefore, early gapping loads have been proposed to provide a clinically more relevant estimation of repair competence compared with the ultimate load in static linear testing,[5] although its visual determination is imprecise.[6]

Cyclic testing is more uncommon than static linear testing when investigating the biomechanical properties of flexor tendon repair. Cyclic testing is time-consuming, but the repetitive loading resembles the postoperative clinical loading of the tendon repair better than static linear testing.[5,7–10] The aim of this cyclic testing study was to compare the gapping behavior of repairs that withstood early loading but eventually failed with those that withstood the cyclic loading without failure. We hypothesize that the onset of plastic deformation and any gap formation during cyclic loading inevitably results in the failure of the tendon repair if the cyclic loading is continued.

METHODS

Samples

Thirty-five frozen thawed porcine flexor digitorum profundus tendons of the second ray (FDP-II) were used in this study. The properties of porcine FDP-II tendons have been shown to be comparable with human flexor tendons.[11] The specimens were the same as those utilized in our previous study.[5] Because the study setting does not enable power calculation, the number of the specimens represented a convenience sample. In brief, the tendons were dissected from the middle segment of the tendon and the dimensions were measured using calipers. The cross-sectional areas of the tendons were calculated ($A = \pi * ab$, where a is the semiminor axis and b the semimajor axis). Each tendon was cut with a surgical scalpel and repaired by the same resident hand surgeon (L.L.). The repair was executed using 2 Pennington-modified Kessler sutures[12] with a 4-0 braided polyester thread (Ethibond Excel; Ethicon, San Lorenzo, Puerto Rico) as the core suture and a 9-purchase over-and-over suture configuration with a 6-0 polyamide monofilament (Ethicon) as the peripheral repair (Fig. 1). The repaired tendons were kept moist in saline-soaked gauzes except when measured. Approval of an ethical board was not needed for this study because no living animals were involved.

Biomechanical testing

Biomechanical testing of the specimens was performed using a material testing machine (LR 5 K; Lloyd Instruments Ltd, Hampshire, UK) connected to a computer with NEXYGEN software (Lloyd Materials Testing, AMETEK, Inc., Berwyn, PA). The repaired tendons were secured to the testing machine with clamps 30 mm apart from each other.

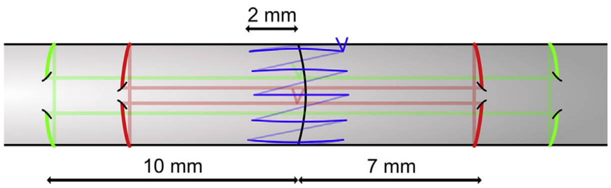

FIGURE 1: A schematic illustration of the repair method. Red and green lines: 4-strand Pennington modified Kessler core suture; blue lines: a 9-purchase over-and-over peripheral suture.

The repaired tendons were loaded in a cyclic manner, with the maximum cycle count being 500. Five hundred cycles correspond to 5 to 10 days of active rehabilitation, and according to an animal model, the biological strengthening only starts thereafter.[3] In addition, 500 cycles have been proven to be sufficient to indicate the possible failure of the repair in a similar testing setting.[10] Based on the excursion of the FDP-II tendon in its sheath during normal finger flexion (11.8 mm)[13] and finger flexion time during rehabilitation, the velocity of the loading was set to 300 mm/min. The lower limit for the load was 0 N in all tests. The upper limits ranged from 17.0 N to 61.9 N and covered the whole range of loads both under and over the anticipated static yield load. The constant upper limit for the load was randomly adjusted for each specimen. Each specimen was tested using only a constant upper limit for the load: the load changed repeatedly between 0 N and the chosen upper limit (eg, 31.1 N) during testing. The specimens either sustained the 500 cycles—after which the testing ended—or it failed during the testing. No further load-to-failure testing was used. The tendon repair was identified as failed when there was no resistance even though extension increased. Failure modes (suture break, suture pull-out, knot unravel) were assessed.

Time-extension graphs were formed for each specimen (Fig. 2). In specimens that sustained the first 50 cycles, the local lowest bound of the extension built up rapidly during the first cycles, but eventually leveled off, obeying the power law (Fig. 2).

Among the tests, there were specimens in which a sudden increase of the total extension was observed. After this point of change, the lowest bound of the extension increased linearly until the failure of the repair. In the present study, this point is referred as the fatigue point. The fatigue point can be determined mathematically by fitting a piecewise-defined function to the minimal extensions of the test. The more detailed statistical methodology is explained in Appendix A (available on the *Journal*'s Web site at www.jhandsurg.org).