In Vitro Cyclic Tensile Testing of Combined Peripheral and Core Flexor Tenorrhaphy Suture Techniques

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Early tenorrhaphy mobilization increases repair site strength and decreases adhesions. Preliminary unpublished data suggest that early active mobilization improves clinical outcome compared with traditional passive motion protocols. We loaded cadaver flexor profundus tendon repairs to 8.0 kg (78.4 N) for up to 5,000 cycles to simulate the loads and cycle number of our active flexor tendon rehabilitation protocol. 3–0 Ethibond (Ethicon, Somerville, NJ) and 6–0 Prolene (Surgipro; US Surgical, Norwalk, CT) were used for core and peripheral sutures, respectively. Four different groups were tested: 2-strand Tajima core suture with either a running interlocking (2R) or a Silfverskiöld cross-stitch (2S) peripheral suture and 4-strand Tajima plus horizontal mattress core suture with either a running interlocking (4R) or a Silfverskiöld peripheral suture (4S). Repairs failed in the suture midsubstance or at the knot. There was considerable variability within groups and no significant difference in the number of cycles to failure between the 2R, 4R, and 2S repairs, which failed after 22,304 ± 249, and 560 ± 987 cycles, respectively. All 4S repairs were intact after 5,000 cycles. Our data suggest that flexor tenorrhaphy with the 4S repair can withstand the cyclic loads we estimate would be present during an active rehabilitation protocol. (J Hand Surg 2002;27A:518-524. Copyright © 2002 by the American Society for Surgery of the Hand.)

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Postoperative mobilization of repaired flexor tendons in zone II was pioneered by Kleinert and others to prevent adhesions and improve tendon gliding.1–5 Tensile properties are enhanced by tenorrhaphy mobilization compared with immobilized repairs.6–12 Better tendon excursion and improved tensile properties have been observed with active mobilization compared with passive methods.12,13 Unpublished data suggested that the outcome of human flexor tendon repair was better when an active rehabilitation program versus passive motion was incorporated (Idler et al, presented at the 55th Annual Meeting of the American Society for Surgery of the Hand, Seattle, WA, 2000).

To incorporate active mobilization into a flexor tendon rehabilitation program, the tenorrhaphy must be able to withstand active loads. The number of core suture strands has been shown to be proportional to the ultimate load of a flexor tendon repair.14–16 Strickland16 estimated that a 4-strand core suture is the least number of strands necessary for an active mobilization rehabilitation protocol. Although pe-
Peripheral sutures have been recommended to tidy the repair and to limit gap formation, their importance in load bearing has only partially been explored. Silfverskio¨ld’s load-to-failure data showed that the cross-stitch peripheral repair alone was stronger than a Kessler core suture reinforced by a running peripheral suture technique. Preliminary clinical data suggest that a 2-strand core and Silfverskio¨ld cross-stitch technique can withstand the rigors of active rehabilitation. We tested the 2- and 4-strand repairs with different permutations of peripheral suture techniques and hypothesized that a 2-strand core suture with the Silfverskio¨ld cross-stitch could be comparable with a 4-strand repair technique. The tensile properties of 2- and 4-strand core tenorrhaphies using running interlocking or Silfverskio¨ld cross-stitch peripheral repair techniques were tested. We used a cyclic loading protocol to simulate load magnitudes and cycle numbers believed to occur during active rehabilitation.

Materials and Methods

Twenty-eight fresh human cadaver index, middle, and ring finger profundus tendons were harvested, lacerated, and repaired by one surgeon with 4 different standardized techniques. The repair technique and tendon used were randomized. 3–0 Ethibond (Ethicon, Somerville, NJ) and 6–0 Prolene (Surgipro; US Surgical, Norwalk, CT) were used for the core and peripheral sutures, respectively. The core sutures were either 2-strand Tajima or 4-strand Tajima plus a horizontal mattress. The peripheral sutures were either running interlocking or Silfverskio¨ld cross-stitches. (Fig. 1). Four groups with 7 tendons in each group were tested with all possible combinations of core and peripheral suture techniques: 2-strand (Tajima) core suture with either a running interlocking (2R) or a Silfverskio¨ld cross-stitch (2S) peripheral suture and 4-strand (Tajima plus horizontal mattress) core suture with either a running interlocking (4R) or a Silfverskio¨ld peripheral suture (4S). Tajima stitches were placed by using double-armed sutures, first placing the transverse limb 0.75 cm from the laceration and then passing the longitudinal limbs out the tendon ends. One suture was used for each tendon end and knots were tied within the repair site. This technique minimizes fraying that occurs when sutures are placed directly into the tendon end. Four-strand repairs were made by placing the Tajima stitch peripherally and the horizontal mattress suture centrally. The running interlocking peripheral stitch and the Silfverskio¨ld cross-stitch throws were placed 0.3 and 0.5 cm from the tendon repair site, respectively. The number of peripheral throws for each repair was recorded. Before laceration intact tendon segment length was measured and tendon segment volume was measured by water displacement. Tendon cross-sectional area was calculated from these values.

Biomechanical Testing

Rationale. Schuind et al showed that in vivo tendon loads for active unresisted finger flexion and light grip were 3.5 kgf (34.3 N) and 7.0 kgf (68.6 N), respectively. Loads most likely would be higher in the injured digit because of edema, friction, and joint stiffness (Chia et al, presented at the 52nd Annual Meeting of the American Society for Surgery of the Hand, 1997). For immobilized tendons there is an ~50% loss of tenorrhaphy tensile strength from that of the initial repair during the first week after repair. In this study we assumed the tenorrhaphy should withstand loads of 8.0 kgf (78.4 N) to
tolerate active unresisted mobilization. This load tolerance provides a safety margin for the potential 50% nadir in tensile strength, or if load increases because of edema, friction, or poor patient compliance.

We estimated that during our active mobilization flexor tendon rehabilitation protocol the tenorrhaphy would be cyclically loaded 120 times per day during exercises consisting of tenodesis and place and hold. During a 6-week rehabilitation period this would amount to approximately 5,000 cycles.

**Testing Protocol.** Repaired tendons were placed in a temperature-controlled saline bath at 37°C. One tendon end was affixed to a stationary clamp and the other to the lever of a dual-mode servomotor (model 6400; Cambridge Technology, Watertown, MA). The motor was interfaced with a computer by software that allowed direct measurement and recording of tendon loads (Superscope II; G.W. Instruments, Watertown, MA). The motor was set to exert sinusoidal cyclic loads of 8.0 kg (78.4 N) up to 5,000 cycles, 4 seconds per cycle. During testing tendons were observed with a high-resolution video camera to dynamically assess gap formation and mode of failure. Tenorrhaphy failure was defined as catastrophic rupture or gapping rendering the repair unable to transmit the force applied.

**Statistics**

Mechanical data were analyzed in 2 ways. Number of cycles to failure was compared among the 4 groups by one-way analysis of variance (ANOVA). Because the 4S group samples all survived to 5,000 cycles and thus had zero variability, this group was excluded from the ANOVA because it would artificially produce a significant result. The remaining 3 groups were subjected to ANOVA with a significance level of .05. In cases in which comparisons showed no significant differences, statistical power was calculated to be ~65%. In these cases statistical power calculations showed that the low power was a result of high intersample variability rather than low sample size. Originally the study was designed based on pilot data to have a group size of 5 tendon repairs per group for a statistical power of 85%. Because the measured variability with this group size measured <85%, group size was increased to 7. Despite increasing experimental group size, power was calculated to be ~65%.

To compare the 4S groups with the remaining 3 groups, one-sampled t-tests were used with each group compared with the number 5,000.

To provide insights into possible structural bases for the mechanical results observed, correlation analysis was used to quantify the correlation between the number of peripheral suture throws and number of cycles and the tendon cross-sectional area and the number of cycles in the 2S, 2R, and 4R groups. Again, the 4S group was excluded because there would possibly be the false conclusion that peripheral suture throw number or tendon cross-sectional area did not correlate with cycle number because all of the 4S repairs survived to 5,000 cycles.

**Results**

The 2R, 4R, and 2S repairs failed at means of 2 ± 2, 304 ± 249, and 560 ± 987 cycles, respectively. None of the 4S repairs failed despite 5,000 cycles (Fig. 2). (Pilot tests not included in these data had one 4S repair that failed at 4,010 cycles and one 4R repair that survived 5,000 cycles.) Because of the high degree of variability, the 2R, 2S, and 4R groups were not statistically different. Comparison of the 4S group with the other groups, however, showed a significantly increased number of cycles to failure (p < .001). Tendons failed at either the suture knots or in the midsubstance.

Tendon cross-sectional area averaged 0.13 ± 0.02 cm². There was no significant difference in profundus tendon area across the 4 repair groups (p > .5) and no significant correlation between cross-sectional area of the tendon and cycle number to failure.
for all groups together (p > .1) or for each group individually (p > .25).

The number of peripheral suture throws in the 2R and 4R groups averaged 12 ± 0.76 (range, 10–12) and 12 ± 0.75 (range, 11–13), respectively. Peripheral suture throw number in the 2S and 4S groups averaged 15 ± 1.4 (range, 14–18) and 17 ± 1.8 (range, 16–21), respectively. There was a strong correlation between cycles to failure and number of peripheral throws in the 4R group (correlation coefficient, 0.881; p = .021) and a negative correlation in the 2R group (correlation coefficient, −0.764; p = .046). There was no correlation between throw number and cycles to failure within the 2S group (correlation coefficient, 0.362; p = .476), and the 4S group could not be assessed because no failures occurred after 5,000 cycles.

Three types of gapping were observed: catastrophic gapping (frank failure); oscillatory gapping (tendons gapped under load but when the load decreased, the gap closed completely); and residual gapping (after multiple cycles, a gap remained even after the load was released). All 2R repairs failed with catastrophic gapping after only a few cycles. The 4R repairs failed by starting with oscillatory gapping early during cyclic testing, progressing to increasing residual gapping and then catastrophic rupture. The pilot 4R repair that completed 5,000 cycles intact had a residual gap of 1 mm. Failures in the 2S group were characterized by either early catastrophic rupture or were devoid of any gap during early cycling, progressing to oscillatory gapping and residual gapping followed by catastrophic rupture. All 4S repairs early in cyclic testing either had oscillatory or no gapping. Four 4S repairs developed residual gaps by the end of 5,000 cycles that were <1 mm. All 4S repairs developed oscillatory gapping at some point during testing. The repairs that started to have oscillatory gapping early in the cyclic testing were the ones that ended with residual gaps.

Discussion

The beneficial effect of tendon motion on tenorrhaphy tensile properties, adhesion formation, and clinical outcome is well appreciated.\(^{5,10,12,31}\) Recently, active tenorrhaphy mobilization has been emphasized over passive methods.\(^{14,16,18,32,33}\) Unpublished data show improved clinical outcomes in patients who had active rehabilitation compared with patients who had a traditional passive protocol after primary flexor tenorrhaphy in zone II (Idler et al, presented at the 55th Annual Meeting of the American Society for Surgery of the Hand, Seattle, WA, 2000).

In an active rehabilitation program the repair must tolerate the loads of active mobilization. Schuind et al\(^{24}\) measured in vivo tendon forces during passive mobilization, active pinch, and grasp in patients undergoing carpal tunnel release under local anesthesia.\(^{24}\) These data are the best estimate of in vivo tendon forces, but the loads in repaired human digital flexors are unknown. The loads are probably higher than those measured by Schuind et al because of the influence of edema, tendon adhesions, repair site friction, and joint stiffness (Chia et al, presented at the 52nd Annual Meeting of the American Society for Surgery of the Hand, 1997).\(^{25–27}\) We believe a tenorrhaphy undergoing an active rehabilitation protocol must at least resist the loads of active unresisted digital flexion with a cushion to accommodate the poorly understood factors that could increase loads beyond the magnitudes shown by Schuind et al.\(^{24}\)

Tendon repairs that have been immobilized lose approximately 50% of their initial repair strength in the first week. Early recovery of tensile strength is manifest by 21 days after repair.\(^{16,28,30}\) Mobilized tendon repairs most likely do not have the same tensile nadir as immobilized repairs.\(^{12,34}\) It is possible, however, that the repair site in some mobilized tenorrhaphies becomes stress-shielded by adhesions proximal and distal to the repair. In this scenario the repair site may behave as if it were immobilized and have similar tensile property behavior as an immobilized tendon repair. We therefore agree with Strickland’s view\(^{16}\) that an actively mobilized tenorrhaphy should be able to withstand at least 2 times the loads of active unresisted flexion, which is at least 7.0 kgf (68.6 N).

The influence of the core suture on tenorrhaphy tensile properties has been emphasized,\(^{14–16,33}\) whereas less consideration has been given to the load-bearing role of the peripheral suture.\(^{15,17–20}\) We focused on the potential major load-bearing role of the peripheral suture when combined with 2- and 4-strand core sutures, contrasting the Silfverskiöld cross-stitch with the running interlocking suture technique.

None of the 2R, 2S, and 4R repairs reliably tolerated the load for the number of cycles to which we estimated a tenorrhaphy would be exposed during our active rehabilitation protocol. Only the 4S repair consistently withstood the rigors of this simulated rehabilitation regimen. There was no significant dif-
ference in cycles to failure between the 2R, 4R, and 2S repair types.

Although there was a trend for increasing cycles to failure in the 2R, 4R, and 2S repairs, the intragroup variability did not permit statistical significance to be achieved. Increasing the group size from 5 to 7 did not influence the lack of significance between groups. Based on pilot data we had initially calculated the group size to be 5 for a statistical power of 85%. After performing the experiment with this group size and not achieving significance between the 2R, 4R, and 2S groups, we increased the group size to 7. Initially we suspected that an uncontrolled variable might account for the intragroup inconsistency. We evaluated 2 such variables, tendon cross-sectional area and number of peripheral suture throws within each group, which did not account for the intragroup variability. There was no correlation between tendon cross-sectional area and cycle number within any of the groups. Although there seemed to be a positive correlation between the number of peripheral suture throws in the 4R group, there was no correlation in the 2S group and a negative correlation in the 2R group.

We believe that the minimal range in throw number in each group prevents meaningful conclusions from being drawn from these data. Most likely, there would be a significant correlation between cycles to failure and peripheral suture throw number if the throw number range was larger. Previous work supports the concept that peripheral suture throw number positively alters the biomechanical properties of the repair. It is possible that peripheral suture throw number and not the technique accounts for the difference in tensile properties between the 4R and 4S repairs. The average number of peripheral suture throws in the 4R repairs was 12 and in the 4S repairs was 17. These numbers may indirectly reflect a difference in the suture technique in that it may have been easier to get an increased number of peripheral suture throws across the repair site with the Silfversköld technique than the running technique.

The size and tensile properties of flexor profundus tendons of the index through ring fingers are not different (Lundberg et al., presented at the 43rd Annual Meeting of the Orthopaedic Research Society, 1997). We therefore felt justified in using tendons from these 3 digits interchangeably. Testing was randomized for the digital tendon and repair technique used; therefore, we do not believe that the tendons tested were the source of the variability seen within groups.

A limitation of the study is that the variability within the 2R, 2S, and 4R groups did not allow significance to be reached between groups. Further increasing group size may have resulted in statistical significance. Another study limitation was not controlling for the number of peripheral suture strands crossing the repair.

We observed 3 varieties of tenorrhaphy gapping under cyclic load: oscillatory, residual, and catastrophic. The catastrophic type is functionally the same as frank rupture because, despite some tendon and suture continuity being retained across the repair, the applied loads could not be transmitted across the tenorrhaphy. The oscillatory type of gapping may not be clinically relevant because the gap closes after the load is released. The residual gap that remained after the load was released is ominous because it may be the in vitro simulation of the kind of gap that in vivo compromises tensile properties and may be associated with increased adhesion formation. In single-loading experiments the oscillatory gap may not be distinguishable from what we think is the more clinically pertinent residual gap. Thus the oscillatory gap in a single-load experiment could be interpreted as bad when it may not be. We believe that early tensile behavior of a tendon repair is more accurately simulated by cyclic loading than by “single-pull” experiments. Based on single-pull testing data, a 4R repair should be stronger than the 2R repair and a 4-strand core repair has been reputed to be strong enough to withstand “active” rehabilitation. In our study, however, the 4R repair was still not reliable in resisting the loads we estimated to be physiologic for the number of cycles used in our active mobilization protocol. Despite the limitations of our study we believe that in vitro cyclic loading more closely simulates the in vivo loading profile of a flexor tenorrhaphy than single load-to-failure testing. Although we recognize the usefulness of single load-to-failure experiments, future studies of early tenorrhaphy strength should also focus on cyclic loading. Because of the different types of gapping observed, single load-to-gap experiments could be misleading.

We believe that our model gives a conservative estimate of repair strength because the anticipated progressive strength increase of in vivo healing after 21 days is absent.

Some aspects of repair techniques that influence strength include suture gauge, number of core and peripheral suture strands, depth of suture throws, the peripheral suture technique, and the peripheral suture...
first technique.14–20,33 Tendon repair with increased numbers of strands may involve a law of diminishing returns. As the number of strands increases across the repair site, technique complexity increases, leading to more tendon handling and consequently more adhesions. Excessive suture bulk may result in triggering or cause increased friction.

The 4S repair is relatively simple. The “Chinese finger trap” effect of the peripheral suture tends to invert the tendon edges and tidies the repair. With load, the tenorrhaphy tends to narrow. The observation that the 4S repair bore simulated “active loads” for the necessary number of cycles more reliably than the other repair methods argues for its superior tensile properties and supports its use with a postoperative active rehabilitation program. Our results support the notion that the 4S is stronger than the 4R technique and that the peripheral suture can bear major load; controlling for the peripheral suture throw number would have made this argument more compelling.

References