Suture techniques with high breaking strength and low gliding resistance

Experiments in the dog flexor digitorum profundus tendon

Toshimitsu Momose, Peter C Amadio, Chunfeng Zhao, Mark E Zobitz, Paulus J Couvreur and Kai-Nan An

Biomechanics Laboratory, Division of Orthopedic Research, Mayo Clinic and Mayo Foundation. Correspondence: Dr. Peter C. Amadio, Mayo Clinic, 200 First Street S.W., Rochester, MN 55905, USA. E-mail: pamadio@mayo.edu
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ABSTRACT – We studied the breaking strength and gliding resistance between the pulley and flexor tendon for various suture techniques. Canine flexor digitorum profundus tendons were transected and sutured using one of eight repair techniques: modified Kessler (MK); Tsuge (Tsuge); two variations of a double modified Kessler (DK1, DK2); combined modified Kessler-modified Tsuge (MKT); augmented Becker (Becker); Cruciate (Cruciate); and modified double Tsuge (DT). The force to produce a 1.5 mm gap, ultimate failure load, resistance to gap formation, and gliding resistance were measured. The force to produce a 1.5 mm gap and the ultimate breaking force were higher with the DK1, DK2, MKT, Becker, Cruciate, and DT repairs than they were with the MK and Tsuge repair, while the gliding resistance of the Becker was higher than that of the MK, DK1, DK2, MKT, Cruciate, and DT repairs. In addition to confirming that repair strength increases as the number of strands crossing the repair increases, we also found that these stronger repairs need not produce higher gliding resistance than less robust repairs.

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Many techniques for flexor tendon repair have been developed over the years. Traditional suture techniques, such as the Kessler (1973), Kleinert et al. (1973), Tsuge et al. (1977), are widely used, and the modified Kessler technique is preferred by many hand surgeons (McCarthy et al. 1995, Papandrea et al. 1995). Early controlled passive or active motion has replaced total immobilization for the postoperative treatment of flexor tendon injuries (Horii et al. 1992, Aoki et al. 1997). Experimentally, it has been shown that early mobilization enhances tendon healing and significantly reduces formation of adhesions (Gelberman and Manske 1985). However, obvious risks arise when applying distraction forces to a repaired flexor tendon before completion of the healing process (Horii et al. 1992). Gapping at the repair site or even suture rupture will greatly diminish the repair and healing process.

To achieve a breaking strength which exceeds light grasping and pinching forces, newer suture techniques with increased holding ability, such as the Becker (1978) marginal suture, the double-loop locking suture (Lee 1990), the 6-strand Savage suture (Savage and Risitano 1989), and cruciate repair (McLarney et al. 1999, Barrie et al. 2000) have been developed. The classic Kessler method has also continued to be modified. The original Kessler method has two knots outside the repair site, while the modified Kessler method incorporates the knot within the repair site (Pennington 1979). The Tajima (1984) suture method is similar to the modified Kessler, with two knots inside the repair site. Singer et al. (1998) performed the double modified Kessler (4 strands) with one knot outside the repair site. Winters et al. (1998) tested an 8-strand modified Kessler method with one knot inside the repair site using a double-stranded suture. The Tsuge suture has also continued to be modified. Tsuchida et al. (1993) used a double Tsuge method (4 strands) with two knots outside the repair site. Yoshizu et al. (1997) and Kusano

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et al. (1999) combined the Tsuge and double modified Kessler methods (6 strands) with one knot outside the repair site and one knot inside the repair site, using double stranded suture. Lim and Tsai (1993) described a 6-strand double Tsuge modification.

Although multiple-strand suture techniques were developed to improve breaking strength, confounding the issue of tendon repair is the finding that the work of flexion increases as the amount of suture material at the repair site increases (Aoki et al. 1995). High gliding resistance disturbs tendon excursion and may lead to increased formation of adhesions. This may explain why the superior performance of multiple strand repairs in vitro has not been reflected in an improvement in clinical results using these methods in vivo (Chow et al. 1987, Pribaz et al. 1989, Winters et al. 1998). We measured the breaking strength and gliding resistance of eight repair methods in vitro, to identify suture methods combining high breaking strength with low gliding resistance which might then be tested in vivo.

Animals and methods

Specimen preparation

160 flexor digitorum profundus (FDP) tendons from the hindpaws of 20 adult mongrel dogs weighing 20–25 kg were used. The dogs had been killed for other purposes, not involving the hind legs. The anatomical structure of the hindpaw FDP tendon is similar to the forepaw FDP tendon (Seiler et al. 1997). The second, third, fourth and fifth digits of each hindpaw were dissected. The synovial sheath around the pulley was removed and a mark was made on the surface of the FDP just distal to the A2 pulley with the digit in full extension. The tendon then was pulled proximally to full flexion of the proximal and distal interphalangeal joints and the tendon was marked again, just distal to the A2 pulley. This distance represented the physiological excursion of the tendon beneath the A2 pulley during full finger motion. The synovial membrane, flexor superficialis tendon, and other pulleys were removed and the FDP, A2 pulley, and proximal and middle phalanx were preserved. The FDP was divided at its insertion on the distal phalanx and the digits were disarticulated at the metatarsophalangeal joint.

Suture methods

80 tendons were used to measure breaking strength and 80 tendons were used to measure gliding resistance. The right digits were used for breaking strength, while the left digits were used for gliding resistance. The tendons were cut at the midpoint of excursion, using the distal edge of the proximal phalanx annular pulley as a reference point, and then one of eight randomly assigned repair techniques was performed. All repairs used either a 5-0 Supramid core suture (5-0 looped monofilament suture composed of polymer nylon, S. Jackson, Alexandria, VA), or a 5-0 Ethilon core suture (Monofilament nylon suture, Ethicon, Somerville, NJ). All repairs included a 6-0 Prolene running peripheral suture (Monofilament polypropylene suture, Ethicon, Somerville, NJ). The repair techniques were (Figure 1):

A) Modified Kessler, 2 strands, with the knot inside the repair site.
B) Tsuge, 2 strands, with the knot placed on the volar surface of the tendon. The width of the locking loop was 1/3 the tendon width.
C) Double modified Kessler method 1, 4 strands, with two modified Kessler sutures and two knots in the repair site. For each of the two sutures, the needle passed through the tendon transversely 6mm from the cut tendon end on one side, while on the other side, the needle passed through the tendon transversely about 3 mm from the other tendon stump. Therefore the two sutures overlapped, a variation of the far-near-near-far technique.
D) Double modified Kessler 2, 4 strands. The modified Kessler repair was performed using a double strand looped suture.
E) Combined modified Kessler-modified Tsuge, 4 strands. The modified Kessler suture was placed first, followed by the Tsuge suture, with the knot within the repair site.
F) Augmented Becker (Singer et al. 1998), 4 strands, with 2 knots outside the repair site.
G) Cruciate repair (McLarney et al. 1999), 4 strands, with the knot buried within a slit 6 mm distal to the laceration.
H) Modified double Tsuge method (Lim and Tsai

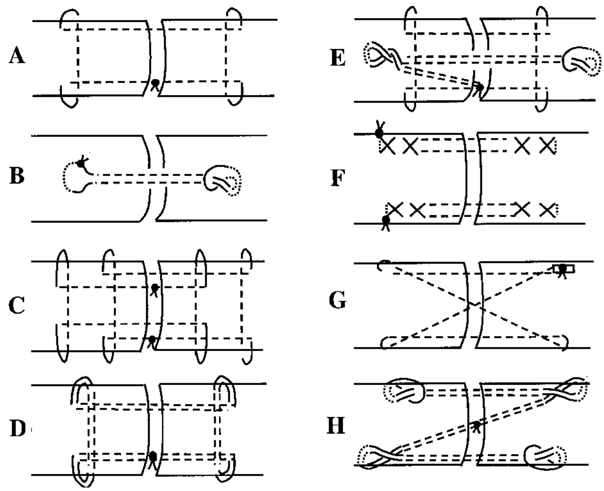

Figure 1. Schematic drawings of the eight suture methods. 5-0 looped Supramid (monofilament nylon) and 5-0 Ethilon (monofilament nylon) were used for core suture. 6-0 Prolene (monofilament polypropylene) was used for the peripheral running suture.
A. Modified Kessler.
B. Tsuge suture.
C. Double modified Kessler 1.
D. Double modified Kessler 2.
E. Combined modified Kessler-modified Tsuge method.
F. Augmented Becker.
G. Cruciate repair.
H. Double modified Tsuge method.

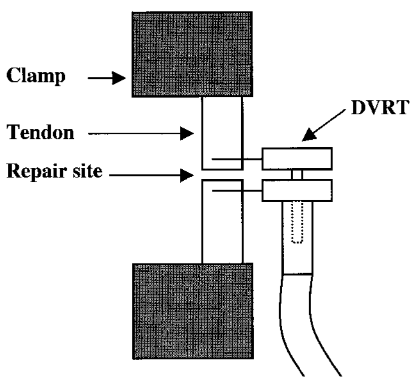

Figure 2. The MTS machine delivered a constant displacement of 20 mm/min to the repaired tendon. A linear displacement sensor (DVRT) spanned the repair site to record suture gap formation. Suture gap and applied load were monitored by a computer.

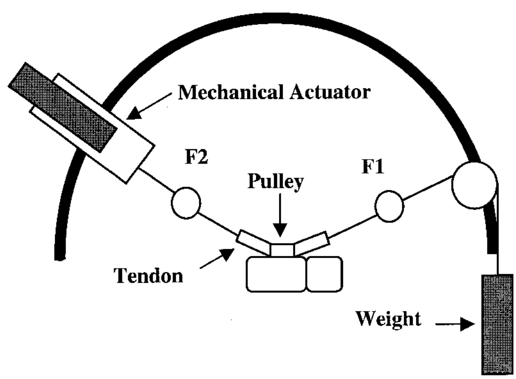

Figure 3. Illustration of the measurement of gliding resistance between tendon and pulley. Tension F1 and F2 were measured by the tensile load transducer. The tendon was pulled proximally by the actuator against the weight.

1993), 6 strands. A modified Tsuge suture was made on both lateral sides (rather than on the volar surface) with the knot inside the repair site.

Breaking strength test

Breaking strength of the eight suture methods was measured with a servohydraulic-testing machine (MTS, Minneapolis, MN). The tendon ends were secured to the test machine using specially designed clamps. A differential variable reluctance transducer (DVRT) (Microstrain, Burlington, VT) was attached to the tendon, spanning the laceration (Figure 2). The DVRT is very small and lightweight and should not adversely affect the tendon failure mechanism. Since the transducer measures displacement between its insertion points, it is an indirect measure of gap formation. Under displacement control, tension was applied to the tendon at a rate of 20 mm/min until complete tendon rupture occurred. The load to produce a 1.5 mm gap, the ultimate failure load, and the resistance to gap formation, a measure of repair stiffness, in units of N/mm, were obtained from the force versus gap relationship.

Gliding resistance test

The digits of the other specimens were fixed with the PIP joint in an extended position, using a 1.5 mm k-wire. Each specimen was mounted in a previously described and validated gliding resistance testing machine (Uchiyama et al. 1995) (Figure 3).

Mean, *Standard Deviation,* and (95% confidence intervals)

	1.5 mm gap force (N)	Ultimate force (N)	Resistance to gap formation (N/mm)	Mean gliding resistance (N)	Maximum gliding resistance (N)
MK	20 *4.1* (17–22)	22 *4.0* (20–25)	26 *8.5* (21–31)	0.27 *0.05* (0.24–0.30)	0.74 *0.23* (0.59–0.89)
Tsuge	19 *2.1* (18–21)	20 *3.0* (19–22)	23 *4.0* (21–26)	0.43 *0.09* (0.38–0.48)	1.1 *0.27* (0.91–1.2)
DK1	30 *5.1* (27–33)	33 *5.6* (30–37)	37 *13* (29–45)	0.31 *0.08* (0.26–0.36)	1.0 *0.15* (0.93–1.1)
DK2	24 *5.2* (21–27)	30 *6.6* (26–35)	36 *16* (26–46)	0.33 *0.04* (0.30–0.35)	0.93 *0.20* (0.81–1.1)
MKT	29 *8.5* (24–34)	31 *8.9* (26–37)	34 *12* (27–42)	0.34 *0.10* (0.28–0.40)	1.1 *0.31* (0.88–1.3)
Becker	25 *5.4* (22–28)	30 *2.5* (29–32)	31 *5.9* (27–34)	0.58 *0.13* (0.50–0.66)	1.3 *0.35* (1.1–1.5)
Cruciate	25 *3.9* (22–27)	31 *9.2* (27–32)	30 *6.3* (25–34)	0.38 *0.07* (0.34–0.42)	0.92 *0.25* (0.76–1.1)
DT	30 *7.3* (25–34)	36 *7.4* (31–41)	35 *13* (27–43)	0.32 *0.10* (0.26–0.38)	0.87 *0.29* (0.69–1.1)

Tensile load transducers were attached to the distal (F1) and proximal (F2) tendon ends. The proximal transducer was attached to the mechanical actuator and the distal transducer was attached to a 500 g weight.

With the arc of contact between the tendon and pulley fixed at 50 degrees, the tendon was moved toward the actuator (flexion) for the predetermined physiological excursion, while load on the distal (F1) and proximal (F2) ends and the tendon excursion were recorded. Then the actuator was reversed to simulate extension and the load and excursion were recorded again. Throughout testing the tendon and pulley were immersed in a saline bath. The gliding resistance between the tendon and pulley was summarized as the mean differences between the F2 and F1 loads for both excursion directions at corresponding excursion points.

Before laceration, the gliding resistance of the intact flexor tendon was measured for a baseline control. Mean and maximum gliding resistance during the full excursion range were calculated.

Analysis of data

Values for gliding resistance were normalized by calculating the difference between the intact and sutured values for each tendon. Mean values of gliding resistance intact tendons ranged from 7.3 to 19 gram-force, while maximum values ranged from 10 to 35 gram-force. To detect differences in force required to generate a 1.5 mm gap, ultimate failure force, resistance to gap formation, and gliding resistance among the repair methods, a one-way analysis of variance was used followed by a Fisher PLSD test. The level of statistical significance was set at 0.05.

Results (Table)

Breaking strength studies

The forces to produce a 1.5 mm gap using the double modified Kessler, double modified Kessler 2, combined modified Kessler-modified Tsuge, Becker, Cruciate, and modified double Tsuge method suture techniques were higher than those needed to produce a gap with the modified Kessler and Tsuge methods ($p < 0.01$). The forces to produce a 1.5 mm gap using the double modified Kessler and modified double Tsuge method suture techniques were higher than the double modified Kessler 2, Becker, and Cruciate suture methods ($p < 0.01$). There were no statistically significant differences between the double modified Kessler and the modified double Tsuge method. Likewise, the ultimate breaking forces of the double modified Kessler, double modified Kessler 2, combined modified Kessler-modified Tsuge, Becker, Cruciate, and modified double Tsuge method repairs were higher than those for the modified Kessler and Tsuge method ($p < 0.01$). The ultimate breaking strength of the modified double Tsuge method repair was higher than that of the double modified Kessler 2 repair ($p < 0.05$). There were no statsistically significant differences in ultimate force among the other multiple-strand repairs.

We observed that breakage and pull-out of the running suture from the tendon stump generally preceded gapping at the repair site. Failure of the repair occurred either by suture breakage or suture pull-out from the tendon stump. In 2 of the 10 Tsuge repairs, the looped suture pulled out from the tendon end. In 3 of the 10 modified double Tsuge method repairs, suture breakage and pull-out both occurred. In 1 of the 10 double modified Kessler 2 repairs, pull-out occurred. All other repairs failed by suture breakage.

The resistance to gap formation using the double modified Kessler, double modified Kessler 2, combined modified Kessler-modified Tsuge, and modified double Tsuge method repairs was higher than that of the Tsuge repair ($p < 0.05$). There were no statistically significant differences between the other repair techniques.

Gliding resistance studies

The mean gliding resistance of the Becker repair was higher than that of the modified Kessler, double modified Kessler, double modified Kessler 2, combined modified Kessler-modified Tsuge, Cruciate, and modified double Tsuge method repairs ($p < 0.05$). The mean gliding resistance of the Tsuge repair was also higher than that of the modified Kessler, double modified Kessler, double modified Kessler 2, combined modified Kessler-modified Tsuge, and modified double Tsuge method repairs ($p < 0.05$). The maximum gliding resistance of the Becker repair was higher than that of the modified Kessler, Tsuge, double modified Kessler, double modified Kessler 2, combined modified Kessler-modified Tsuge, Cruciate, and modified double Tsuge method repairs ($p < 0.05$).

Compared with the other suture methods, the Becker repair had both high breaking strength and high gliding resistance, while the modified Kessler repair had both low breaking strength and low gliding resistance. The Tsuge repair had low strength and high gliding resistance, while the double modified Kessler, double modified Kessler 2, combined modified Kessler-modified Tsuge, Cruciate, and modified double Tsuge method had high breaking strength and low gliding resistance.

Discussion

Multiple-strand suture techniques have a higher breaking strength than repair techniques with fewer strands (Shaieb and Singer 1997, McLarney et al. 1999) and provide a theoretical margin of safety with either early controlled passive (low force) or active (high force) mobilization after flexor tendon repair. However, with a multiple-strand suture method the repair site may become bulky, which could impair passage through the pulley system (Noguchi et al. 1993). In such a case, the increased strength of the repair may be more than taken up by the increased force needed to move the bulkier tendon through the pulley system (Zhao et al. 1999). The result may be impaired tendon gliding (Aoki et al. 1995) and no net improvement in clinical results, despite the extra strength and complexity of the repair (Chow et al 1987, Pribaz et al. 1989, Winters et al. 1998).

We studied the mechanical properties of eight suture methods. Suture methods with low breaking strength and low gliding resistance, like the commonly performed modified Kessler repair, seem well-suited for the also common passive mobilization regimens. The low force applied is unlikely to jeopardize this weaker repair, while the low gliding resistance of the repair helps assure gliding of the repair within the pulley system under the low loads that can be applied with passive mobilization. Such repairs may not, however, be sufficiently strong to permit safe application of active motion rehabilitation protocols. In contrast, suture methods with high breaking strength and high gliding resistance, like the Becker repair, may disturb smooth excursion under the pulley. Such repairs may not function well with passive, low force rehabilitation regimens, since the passive mobilization techniques may not generate sufficient force to overcome the increased gliding resistance. Such repairs may be better suited for active motion protocols, where higher loads can be applied. The increased strength of the Becker repair allows for some margin of safety in applying these higher loads. The ideal combination would seem to be suture methods which combine high breaking strength and low gliding resistance, like the double Kessler 1 and double Tsuge repairs, which may prevent gap formation and induce smooth excursion at lower loads, possibly with either active or passive rehabilitation. The worst combination would seem to be suture methods which combine low breaking strength and high gliding resistance, like the Tsuge repair. Such repairs may not glide under low loads and may fail at higher loads.

Increasing the number of grasping stitches on the tendon surface creates high breaking strength, but also may increase gliding resistance and triggering of the repair site at the entrance to the pulley (Coert et al. 1995). It is likely that irregularity and increased tendon volume at the repair site along with knots and looped suture on the surface of the tendon would not only increase gliding resistance, but also increase the roughness of the surface. This roughness may create a nidus for adhesions either primarily, on the tendon surface, or secondarily, by scoring the pulley surface with repetitive motion. Winters et al. (1998) recently described a new and stronger 8-strand Kessler repair. Gliding resistance was not measured, but motion at 6 weeks in response to a standard load was significantly less for the 8-strand than for 2- or 4-strand repairs.

To reduce gliding resistance, we used a double stranded suture in the DK2, MKT and DT techniques. The use of looped sutures also reduces the amount of tendon handling (Gill et al. 1999) that is needed to perform the repair. In the DK1, DK2, MKT, and DT methods the knot was made within the repair site in a further effort to diminish the gliding resistance.

The strength of our study is that we have been able to isolate and measure the gliding resistance between tendon and pulley. We have used several clinically relevant repair techniques and have shown that some of them combine the favorable characteristics of high breaking strength without increasing friction, while some commonly used repair methods are suboptimal in these regards. This information may be clinically useful. The limitation of our study relates to the fact that it is an in vitro study. Confirmation of our findings in vivo is necessary.

In conclusion, we have shown that multiple-strand suture methods with knots inside the repair site and double stranded suture can increase the strength of tendon repairs without necessarily increasing gliding resistance.

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