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The Quadriga Effect Revisited: Designing a “Safety Incision” to Prevent Tendon Repair Rupture and Gap Formation in a Canine Model In Vitro

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Abstract

Loss of experimental animals due to tendon repair failure results in the need for additional animals to complete the study. We designed a relief proximal to the flexor digitorum profundus (FDP) tendon repair site to serve as a “safety incision” to prevent repair site ruptures and maximize safety incision-to-suture strength. The FDP tendons were dissected in 24 canine forepaws. The 2nd and 5th tendons were lacerated at the proximal interphalangeal joint level and sutured using a modified Kessler technique and peripheral running suture. Tendon width was measured where the FDP tendon separates into each individual digit and a safety incision, equal to the 2nd and 5th tendon widths, was performed 3, 4, or 5 mm (Groups 1, 2, and 3) proximal to the separation. The tendons were pulled at a rate of 1 mm/s until either the “safety incision” ruptured or the repair failed. There was no gap formation at the repair site in Groups 1 and 2. However, all Group 3 tendons failed by repair site rupture with the safety incision intact. An adequate safety incision to protect repair gap and rupture and maintain tendon tension for the FDP animal model should be about 4 mm from where the FDP tendon separates.

Keywords

incision; repair rupture; flexor tendon; gap formation; cross-links

The canine is the most common and useful model for flexor tendon research, both in vitro and in vivo, because of its similarity to human tendon anatomy, structure, and adaptability.^{1–6} Postoperative care and control of the animals are a significant challenge. The canine flexor digitorum profundus (FDP) is one tendon bundle until the distal forepaw level, where it separates into the four tendons to each individual digit. The canine paw is a weight-bearing structure, which is different from the human hand. As a result of inadvertent weight-bearing postoperatively, the rate of gap formation (>3 mm) after repair (30–100%), including ultimate gap and tendon rupture, is higher than that reported in human clinical series (10–50%).^{7–13}

Daily active motion varies from dog to dog and is difficult to control even with external fixation. Routine activities, even within a cast, may still lead to gap formation or repair rupture. The high rate of this complication and the resulting attrition of experimental animals require larger sample sizes and is thus costly in terms of animal welfare and cost.^{14,15}

Better control of repair loading is thus clearly important in flexor tendon research in the canine model. Pruitt et al.¹⁶ reported a modification in which the musculotendinous junction was transected, lengthening the tendon to prevent rupture. However, this procedure would affect digit motion and decrease tendon tension, which might affect healing. Bishop et al. used a radial neurotomy to prevent weight bearing. Although this method minimizes weight bearing, a cast is still needed, and gap formation and tendon rupture still occur.^{2,13}

The function of one tendon will limit the excursion and function of the rest. This principle was termed the “Syndrome of the Quadriga” by Verdan, who compared the common muscle belly of the FDP to the driver of a Roman chariot, the auriga and the four FDP tendons to the reins of his four horses.¹⁷ Having the reins circled around their bodies, the charioteers would guide the horses by moving or bending to their sides. According to this principle, the muscle force will be evenly transferred from one bundle to four digits if the tensions of the four tendons are the same. However, tension transmission among digits could be altered depending on their relative excursion and laxity to their common origin (Fig. 1). If one tendon is shorter than the others, it will receive loading first and perhaps exclusively. Conversely, tendon tension can be decreased by lengthening it.

If a safety incision is made within the common tendon, before it divides into its four slips, tendon length and normal quadriga function might be maintained, while providing a safety mechanism to protect a weak tendon from rupturing. At such location, the force applied to a repaired tendon would be transferred through the collagen cross-links, between the intact longitudinal bundles, within the common tendon distal to the safety incision and proximal to the level at which the tendons separate. Based on this anatomical characteristic, a safe model for FDP tendon repair in dogs and other animals (chicken, rat, mouse, and rabbit) is possible. A similar anatomic situation occurs in humans, of course; a safety incision could also be considered in an uncooperative patient (e.g., a child or comatose individual) sustaining a zone 2 injury.

The purpose of this study was to design a “safety incision” proximal to the FDP tendon repair site in zone 2 to prevent repair site ruptures and maximize *safety incision-to-suture strength*. We hypothesized that, due to the weakness of the cross-links between collagen bundles, this incision would form a gap when the force applied to the tendon reached the level that tears the collagen cross-links (Fig. 2b,c).

MATERIALS AND METHODS

Experiment

Twenty-four forepaws were obtained from adult mongrel dogs sacrificed for other, IACUC approved purposes, and the FDP tendons were dissected. The 2nd and 5th FDP tendons were used for repairs; FDP tendons are the most common digits for research.^{18,19} Tendon width was measured using a caliper where the FDP tendon separates into each individual digit, and a relief incision, equal to the 2nd and 5th tendon widths, was randomly performed at the following levels (Fig. 2a): *Group 1*, 3 mm proximal; *Group 2*, 4 mm proximal; and *Group 3*, 5 mm proximal to the point where the common FDP tendon separates.

Tendons were fully lacerated at the proximal inter-phalangeal (PIP) joint and repaired with a modified Kessler technique using 4-0 nonabsorbable nylon suture (Supramid, S. Jackson, Inc., Alexandria, VA). 6-0 nonabsorbable polypropylene suture (Prolene, Ethicon, Inc., Somerville, NJ) was used for the running peripheral suture, with an average of 10 loops/tendon.

After preparation, the 2nd digit of the FDP tendon was mounted on a material testing device for mechanical evaluation (Fig. 3). The measurement system consisted of one mechanical actuator with a linear potentiometer and one load transducer. The transducer was attached to the proximal end of the tendon and connected to the actuator. The proximal bundle of the common FDP tendon was secured by a specially designed clamp. The distal end of the 2nd digit was secured by another clamp. To detect and measure gap formation, two markers were placed between the safety incision and between the repaired sites. A Motion Analysis System with two cameras captured marker displacements (EvaRT 5.0.3, Motion Analysis Corp., Santa Rosa, CA). The tendon was pulled proximally at a rate of 1 mm/s recording the force readings from the transducer until the tendon failed either at the safety incision or repair site. The force and displacement data were collected at a rate of 20 Hz. A similar procedure was performed on the 5th digit. Throughout testing, the tendons were kept moist by spraying with physiologic saline.

Following testing, tendons that failed at the safety incision and showed no visual gap (zero gap formation) at the repaired site were secured in the same testing machine and distracted to failure at a rate of 1 mm/s. Tensile force and maximum breaking force were recorded. Again the tendons were kept moist by spraying with physiologic saline.

Statistics

In a given paw, distance cuts (3, 4, or 5 mm) were randomly assigned on each side of the 2nd and 5th tendons. A one-way ANOVA was used to assess differences among the three groups for breaking strength and resistance to gap formation. The Tukey post hoc test for multiple comparisons was used to assess differences among incision levels. We achieved a power of 0.8 to detect a significant difference at the 0.05 level with a sample of eight per group.

RESULTS

No significant difference was found in maximum “safety incision” force and suture force between 2nd and 5th FDP tendons with the same incision cut. Of the 24 paws, 14 contained only one usable digit (14 tendons); out of the 20 remaining tendons (10 paws), 10 (5 from Group 1, 4 from Group 2, and 1 from Group 3) were excluded from the analysis based on either duplicate incision cuts on the same tendon or marker displacement error resulting from data acquisition.

All tendons in Groups 1 and 2 failed by tearing the safety incision with zero gap formation or by rupture at the repair site (Fig. 4). However, all tendons in Group 3 failed by breaking the repair site with the safety incision intact. The mean maximum force to break the safety incision in Group 1 was 21.5 ± 7.1 N, which reached about 38% of the maximum force to break the repairs. The mean maximum force of Group 2 was 37.6 ± 8.5 N, which accounted for 57% of the maximum force to break the repairs. No significant difference existed in terms of maximum suture tensile strength among the groups. However, the mean maximum force to break the safety incision in Group 2 was significantly higher than that of Group 1 ($p < 0.05$).

Figure 5 shows an example of the trends experienced by the three groups. Figure 5a,b shows the force versus excursion for the safety incision and the displacement versus excursion of the markers at the incision and at the repair site. Upon failure of the safety incision, a marked increase in displacement occurred. Figure 5c shows the force versus excursion for the suture and the displacement versus excursion of the markers at the safety incision and at the repair site. As the tendon was being stretched, there was visual confirmation of gap formation and suture rupture with no gap formation at the safety incision site. Group 3

confirmed suture rupture and gap formation >2 mm with a safety incision 5 mm proximal to the where the FDP tendon separates.

Safety incision stiffness and suture stiffness were calculated along the force/displacement curves (Table 1). The mean safety incision stiffness for the 3 mm and 4 mm groups was 11.2 and 33.3 N/mm, respectively. The mean suture stiffness (5 mm incision) was 17.4 N/mm.

DISCUSSION

While considerable evidence exists that mobilization is significant to tendon healing, little if any evidence exists that loading, beyond that needed to ensure motion, has any effect on healing.^{14,20–22} Wada et al.²³ found that gap strength and ultimate repair strength were greater in active mobilized tendons than immobilized tendons. However, as FDP tendons bear high load due to weight bearing in the canine, the rupture rate following repair is much higher compared to human clinical results.^{6,9,24} Zhao et al.¹⁴ reported that the canine repair rupture rate could be as high as 50% depending on survival time, immobilization methods, and weight-bearing status. As soon as the immobilization is removed, weight bearing can increase the rupture rate to 100%.¹⁴ Additionally, a 16% failure rate found in nonweight bearing animals is at least double the repair rupture rate reported from clinical studies (from 4% to 13%).^{11,25–31} Moreover, if tendons with a gap >3 mm, having a significant effect on healing,⁹ are considered, failure rates would increase markedly. Whereas a clinical rupture can be re-repaired, animal ruptures typically result in euthanasia with no data being gathered, wasting the animal's life.

Suture failure is caused when applied tension exceeds suture-breaking strength. To avoid failure, prevent gap formation, and protect the healing tendon, strong suture techniques have been developed.^{6,9,24,32,33} Nonetheless, the tendon/suture interface is a common failure point.¹⁵

Other strategies have been developed to minimize loading on the repair, such as radial nerve denervation, fiberglass shoulder spica cast, or sling jacket.^{2,5,13,34,35} However, ruptures still occurred postoperatively, related to the difficulty in controlling animal weight-bearing during cage activity. Tenotomy proximal to the repair site has been used to prevent gap formation or rupture of repairs.^{2,9,16,36} Our “safety incision” model is a variation on this theme, using the anatomical features in the canine to not only prevent the risk of repair rupture but also maintain tension on the repaired tendon, at least until the safety incision breaks. Thus, when loading exceeds the strength limits of the safety incision, the incision fails rather than the repair. The force to cause the tear at the incision is determined by the length of preserved tendon (Fig. 2). The best safety incision is one that absorbs the highest force within the threshold of 2 mm gap formation in the repaired tendon, as gaps >2 mm adversely affect outcome.^{5,6,9} This provides a safer model for FDP tendon repair research and minimizes loss of experimental animals.

In our study, the mechanical setup was designed assuming the worst case, in which all loading is on one tendon of interest. For this reason, during testing, tension was only maintained on the repaired tendon. This reflects the case, for example, of a “tight” clinical repair, in which the repaired tendon may be a millimeter or so shorter than its uninjured fellows.

The maximum repair strength for Group 2 averaged 66 N and maximum failure force for the safety incision was 57% (37.6 ± 8.5 N) of the repair strength. Based on the literature, the force applied to the tendons during rehabilitation ranges from 5 to 30 N in the canine model depending on passive or active therapies³⁷; thus a safety incision of this breaking strength

would accommodate normal rehabilitation without failure, but would fail if greater forces were applied, such as from inadvertent weight bearing.

Our results showed that a safety incision 5 mm from the separation would be too strong, leading to failure of all repairs during testing. Although the safety incision at both 3 and 4 mm distance effectively protected the repair from gap or rupture, a 4 mm safety incision presented a better force threshold. The maximal mean force to tear a 3 mm safety incision was 21.5 N, or 38% of repair strength, which would effectively protect the repair from rupture. However, the force applied to the tendon during rehabilitation or active motion exceeds this threshold, leading to a high risk of safety incision failure during normal rehabilitation. The maximal mean force for the 4 mm incision was 37.6 N, or 57% of the repair failure strength, which would protect the repair from rupture and be tolerant to active motion.

Safety incision stiffness was only calculated in the 3 and 4 mm groups, as both groups showed tendon rupture upon excursion after maximum force was reached. Suture stiffness was only calculated for the 5 mm group, as this group showed repair failure in all samples when tested with the displacement markers. Suture stiffness was 17.4 ± 11.2 N/mm, similar to Yang et al.'s³⁸ suture stiffness results of 16.7 ± 2.8 N/mm. When calculating suture stiffness for the eight samples, two yielded higher stiffness values than the other six. As described by Aoki et al.,⁷ placing the suture knot outside the repair increases ultimate tensile and gap strengths. Though the suture technique was designed to be consistent throughout the experiment, surgical variation will be present.

Suture stiffness was not measured postsafety incision failure of Groups 1 and 2 as suture strength exceeded the tensile force required for breaking the incision. Though Figure 5 shows an ~2 mm displacement of the markers at the repair site when the safety incision was totally torn (Groups 1 and 2), no visual gap formation was noted in the repair. This effect can be attributed to the viscoelastic properties of the tendon.

With a safety incision proximal to the repair site, the suture will be loaded until the load exceeds the suture or safety incision threshold strength. However, this altered loading at the repair site not only protects the suture from failure but also maintains load within the safety incision failure range. Compared to previous animal models that included total tendon tension release or the use of immobilization, our technique provides a better control of repair loading by creating a maximum limit, beyond which the safety incision fails and suture load falls towards zero.^{2,5,9,13,14,16,34-36} If necessary, the integrity and efficiency of the safety incision can be visualized and evaluated by ultrasound imaging.

Studies examining the effects of loading on tendon healing, while mixed, show that it plays a role.^{20-22,36} Tendon and ligament experimental studies demonstrated that both high loads (leading to gaps or ruptures)^{12,21} and low loads (leading to deterioration, mainly through high matrix metalloproteinase activity)^{39,40} are detrimental to healing. However, “low load” conditions mentioned are associated with immobilization. With our method, the tendon could still be mobilized passively after safety incision rupture. Whether mobilization without tension is better or worse than mobilization with low tension remains to be evaluated. This is now possible with our model. If tendons that are mobilized without tension heal with similar strength and adhesions as loaded tendons, it would show that it is motion, rather than loading, that is the key to sound tendon healing. In contrast, if unloaded tendons behave like immobilized tendons, then we would learn that both motion and loading are important, and we would have an idea of the load threshold, namely, the “safety incision” breaking strength. Indeed, by adjusting the breaking strength by the methods described here, various loading thresholds could be studied. Thus, we believe that our safety

incision concept has the potential to affect our understanding of the effect of mechanical loading on tendon healing in vivo.

The safety incision principle, as a preventive method for repair failure, could also be applied to the 3rd or 4th digit. For the border digits, we are relying upon the cross-links between collagen fascicles on only one side of the tendon. Thus, for a central tendon, we would theoretically need 2 mm of cross-links on either side of the tendon to match the repair strength, and therefore we would predict that the safety incision should be made 2 mm proximal to the point where the tendons separate, as opposed to 4 mm proximal for the border digits.

Several limitations were present in the current study. We only looked at three incisions for the design, with the depth equal to the tendon width. Other options in either longitudinal or transverse dimension were not studied, which might provide different outcomes. Also, this was an in vitro study. Safety incision strength may increase with time due to healing in vivo. However, healing would also occur at the repair site, which would cause the repair strength to increase.^{5,41} In addition, we only tested border digits; the ultimate tensile strength of the central digits was not tested. Finally, the current study was designed based on flexor tendon research using an animal model. This method might not be suitable for clinical application. However, one could explore the same mechanism in the human hand, which may be applicable for flexor repair with high risk of postoperative gap or rupture, such as pediatric or comatose patients.

In summary, we explored the use of a “safety incision” concept and quadriga effect to prevent gap formation and suture failure in a canine tendon repair model. We found that an adequate safety incision to protect repair gap and rupture and maintain tendon tension for the FDP animal model should be about 4 mm from where the FDP tendon separates.

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Figure 1.

(a) Dissected canine FDP tendon. One tendon bundle separates into four tendons to each individual digit. (b) According to the “Syndrome of the Quadriga,” muscle force is transferred evenly to the four tendons if their tension is the same (top). During flexion of the 2nd, with all other digits already flexed, most of the muscle force is transferred to the 2nd FDP tendon (bottom). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Figure 2.

(a) A relief incision performed proximally to the repair site to serve as a “Safety Incision” and prevent repair site failure. Variable lengths of incision (safety incision locations) from tendon division and preserved tendon tissue, from where the FDP tendon separates into digits, were represented by Groups 1–3. When muscle force is transferred to the tendon, with all other digits flexed (white arrows), most of the force will be transferred to the 2nd digit (black arrow). Force transmission is altered based on the relief incision. (b) With only the 2nd digit in tension (black arrow) and a safety incision performed, force will be transmitted to and the tendon digit only held in place by the weak cross-link regions (shaded region). (c) When pulled, due to the weakness of the cross-links, the incision will gap and keep the repair intact.

Figure 3.

The FPD tendon was mounted on the tensile tester with two displacement markers located between the safety incision and the repair site. The tendon was pulled proximally by an actuator at a rate of 1 mm/s, and the displacement acquired by two cameras.

Figure 4.
Safety incision performed on a 5th digit (Group 1). When pulled, the safety incision failed by tearing the weak cross-links, forming a gap, and keeping the repair intact.

Figure 5.

Typical force versus displacement for the three groups. Once the safety incision reached its strength threshold, a noticeable displacement of the incision occurred due to tendon tear or rupture (a,b). There was a constant displacement of the suture markers due to suture failure (c). Maximum force threshold is also shown. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Table 1
Summary of In Vitro Experimental Data: Safety Incision and Suture Tensile Properties and Stiffness Analysis^a

Incision Distance (Group)	Total # of Samples (n)	Max. Safety Incision Tensile Strength (N)	Max. Suture Tensile Strength (N)	Safety Incision-to-Suture-Strength (%)	Visual Suture Failure (Yes/No)	Safety Incision Stiffness (N/mm)	Suture Stiffness (N/mm)
3 mm (Group 1)	8	21.5 ± 7.1 *	59.4 ± 14.6 **	37.9 ± 14.9 *	No	11.2 ± 4.7 *	N/A
4 mm (Group 2)	8	37.6 ± 8.5 *	66.4 ± 9.8 **	56.6 ± 9.2 *	No	33.3 ± 6.9 *	N/A
5 mm (Group 3)	8	N/A	55.8 ± 8.0 **	Fails	Yes	N/A	17.4 ± 11.2

^a All values are given as mean ± SD.

* At the 0.05 level, population means are significantly different.

** At the 0.05 level, population means are not significantly different