Received: 3 December 2020 | Revised: 10 May 2021 | Accepted: 22 June 2021

DOI: 10.1111/vsu.13678

ORIGINAL ARTICLE - RESEARCH

WILEY

Ex vivo evaluation of novel core tenorrhaphy patterns in dogs

King Wa Chiu BVSc, Grad. Cert. (Clin Ed), MANZCVS (Small Animal Surgery)[1] | Daniel J. Duffy BVM&S(Hons.), MS, FHEA, MRCVS, Diplomate ACVS-SA, DECVS, RCVS and EBVS Recognized Specialist in Small Animal Surgery[1] | Yi-Jen Chang BVetMed, MS[1] | Lewis Gaffney BS[2] | Matthew B. Fisher PhD[2]

[1]Department of Clinical Sciences, College of Veterinary Medicine, North Carolina State University, Raleigh, North Carolina, USA

[2]Joint Department of Biomedical Engineering, North Carolina State University and the University of North Carolina – Chapel Hill, Raleigh, North Carolina, USA

Correspondence
Daniel J. Duffy, Department of Clinical Sciences, College of Veterinary Medicine, North Carolina State University, 1052 William Moore Drive, Raleigh, NC 27607, USA.
Email: djduffy@ncsu.edu

Funding information
Firestone Canine Research Endowment, Department of Clinical Science, College of Veterinary Medicine, North Carolina State University; Wade O. Brinker Research Award from the Veterinary Orthopedic Society

Abstract

Objective: To compare the biomechanical properties and gapping characteristics of four novel tenorrhaphy patterns in a canine flexor tendon model.

Study Design: Ex vivo, randomized, biomechanical study.

Sample Population: Superficial digital flexor tendons of 60 forelimbs (30 dogs).

Methods: Each tendon was transected 25 mm distal to its musculotendinous junction prior to tenorrhaphy with 2-0 polypropylene. Repair patterns included the three-loop pulley (3LP, control), exposed double-cross-lock (ExDCrL), embedded double-cross-lock (EmDCrL), triple-circle-lock (TCiL), and Modified-Tang patterns (MTang) were randomly assigned to each experimental group ($n = 12$/group). Yield, peak, and failure loads, gap formation and failure modes were compared.

Results: Tendons repaired with ExDCrL ($p < .0001$), EmDCrL ($p < .0001$), and MTang ($p < .0001$) sustained yield, peak, and failure loads ~2.2x, ~2.0x, and ~1.9x, respectively, greater than those repaired with 3LP. Loads to 1 and 3 mm gapping were also higher for ExDCrL ($p < .0001$), EmDCrL ($p < .0004$), and MTang constructs ($p < .0017$) compared to 3LP. Although TCiL constructs sustained higher loads, their resistance to gap formation did not differ from that of 3LP repairs. Failure mode differed between groups ($p < .0001$), EmDCrL, ExDCrL, MTang, and TCiL constructs failing predominantly by suture breakage compared to 3LP repairs that failed by suture pull-through.

Conclusion: Use of novel patterns ExDCrL, EmDCrL, and MTang improved resistance to loads and gap formation and were biomechanically superior compared to 3LP in healthy canine tendon repairs.

Clinical Significance: These results justify in vivo evaluation of ExDCrL, EmDCrL, or MTang pattern for tenorrhaphy in dogs.

1 | INTRODUCTION

Suture tenorrhaphy is often required when tendinous injury is encountered in dogs, regardless of the inciting mechanism or cause, to allow patients to return to normal function.[1] The goal of primary surgical intervention is to restore the tendon's working length and to prevent further elongation.[2] Tendinous healing is a prolonged process with many overlapping phases; therefore, it is important to ensure that the surgical repair has adequate resistance to gap formation, ultimate strength, and stiffness in order to prevent scar tissue formation and failure of tendinous union in canine patients.[3,4]

Tendinous healing is a protracted process—the tensile strength is less than 60% of its original strength 6 weeks after surgery.[5] Gelberman et al. compared the healing response of canine flexor tendons in dogs that were immediately mobilized after surgical repair, 3 weeks after surgery (delayed mobilization) and immobilized for 12 weeks.[6] At the 12-week time point, they showed that ultimate tendon strength of dogs that had immediate mobilization had ~95% of original tendon strength.[6] However, dogs that were immobilized and those that had delayed mobilization only had 19% and 67% of the original tendon strength.[6] Although it is known that early mobility improves tendinous healing,[6] patients are often immobilized using casts, internal or external skeletal fixation.[7–12] One of the reasons for prolonged immobilization is due to suboptimal biomechanical repair strength and concern about early repair site overloading or failure.[7–12]

A biomechanically superior core suture that allows early mobilization may translate to improved cartilage health, collagenous reorganization, and progression of tendinous healing in vivo.[13] Numerous suture patterns used for canine tenorrhaphy have been described, including but not limited to, the three-loop pulley (3LP), locking-loop (LL), Bunnell-Mayer, mattress, continuous cruciate, and simple interrupted patterns.[14–20] Due to the linear orientation of collagen fibrils within the tendon, the holding strength for simple suture patterns is relatively low, potentially resulting in gap formation, suture pull-through, and in some cases clinical failure.[21] Tendons repaired with suture patterns that have a greater degree of interaction between tendinous tissues and suture, for example, 3LP and LL, have improved resistance to suture pull-through.[16,22] As a result, they are considered to be superior in maintaining apposition of tendon ends during load application.[16,22] Multiple studies have compared the biomechanical strength of tendons repaired with 3LP and LL. Berg et al. demonstrated that canine tendons repaired with LL were biomechanically inferior compared to those with 3LP.[14] Since the strength of the final tendon repair is influenced by the number of strands crossing the anastomotic site,[23] Moores et al. compared the 3LP against two LL sutures for tendinous repair.[18] Constructs with two LL sutures had lower resistance to gap formation compared to those with 3LP.[18] Core tendon sutures are suture patterns that provide the majority of the strength at the tenorrhaphy site and are considered to be the strongest component of the repaired specimen.[24] Improving the biomechanical strength and load to gap formation of core tendon suture patterns is therefore an important consideration prior to clinical use.[3,4] In particular, for working dogs that experience greater applied loads at the repair site,[25] Worth et al. reported that 29% of working dogs, following common calcaneal tendon repair using a LL suture, did not return to normal function while demonstrating evidence of persistent ongoing lameness.[25] Gap formation at the tenorrhaphy site greater than 3 mm has an increased risk of tendon rupture.[26] Novel core suture patterns that have greater load to gap formation may improve surgical outcomes. In addition, a stronger repair may theoretically allow earlier weight-bearing and early mobilization.

In human digital flexor tendon repair following an acute laceration injury, multistrand locking core suture patterns, including the augmented Becker pattern and Savage pattern, have been described and utilized successfully by hand surgeons.[27–30] These multistrand locking core suture patterns, placed within the body of the tendinous substance, may be superior regarding their biomechanical characteristics and loads required to cause gap formation compared to techniques currently utilized in canine patients. Greenwald et al. compared the augmented Becker pattern to a modified Kessler pattern in monkeys and showed tendons repaired with augmented Becker to be stronger.[28] Constructs repaired with technique modifications of the Savage suture pattern have also been biomechanically evaluated.[27] Aoki et al. concluded that tendons repaired with six-strand Savage suture using a single outside knotting technique demonstrated superior biomechanical strength and decreased occurrence of gap formation in canine tendinous specimens.[27] Improving the biomechanical properties of core suture repair techniques may result in substantial advances in tendon repair methods by veterinary surgeons compared to traditional repair techniques current utilized following canine tendinous injury.

The objective of this study was to evaluate the ability of four novel patterns to improve the biomechanical properties, gapping characteristics, and failure modes as compared to 3LP pattern in a canine flexor tendon model. We hypothesized that the tendon biomechanics using these novel patterns would be superior compared to those with 3LP, with a smaller gap forming between tendon ends with no difference in failure mode.

2 | MATERIALS AND METHODS

Sixty forelimbs were collected from 30 healthy mix-breed adult dogs greater than 1 year of age, weighing between 27 and 32 kg. Forelimbs were serially acquired immediately following euthanasia using 1 ml/4.5 kg pentobarbital sodium (Beuthanasia, Merck Animal Health, Millsboro, Delaware) administered IV for reasons unrelated to this study. North Carolina State University, College of Veterinary Medicine did not require an Institutional Animal Care and Use Committee (IACUC) protocol for the purposes of this study. A local animal shelter provided the dogs following consented specimen donation. If there was any history of orthopedic disease or abnormalities detected on a focused orthopedic examination by one of the study authors (DJD), dogs were excluded from the study. The superficial digital flexor tendon (SDFT) was carefully dissected from the distal humerus (origin) to the level of the phalanges (insertion).[31] All retinacular tissues on the palmar aspect of the carpus were removed as previously described.[31] After individual labeling, dissected specimens were stored within a thermostatically controlled freezer at −20°C after being wrapped in saline-soaked gauze using a previously validated technique.[32] Prior to testing, specimens were thawed at room temperature (21°C) for approximately 12 h. Each tendon was then sharply transected transversely (perpendicular to the direction of collagen fibril alignment) using a #10 scalpel blade (Shard, Sunnyvale, California) at a measured distance of 25 mm, distal to the musculotendinous junction. A photograph of the distal transected surface of the SDFT was captured (Samsung Galaxy S8 plus, San Jose, California). Photographs were taken parallel to a calibrated ruler for measurement of tendon cross-sectional area (CSA). For each tendon, the CSA was measured a total of four times using a digital imaging software program (ImageJ, National Institute of Health, Bethesda, Maryland). The mean CSA was then calculated for each specimen by a single investigator (KWC).

Using randomization software (https://www.randomizer.org, Randomizer), specimens were assigned to one of five individual treatment groups ($n = 12$/group) controlling the contralateral limb from each dog from being assigned to the same experimental group. An American College of Veterinary Surgeon (ACVS)-SA resident in training (KWC) performed all tendon repairs under the close supervision of an ACVS board-certified surgeon (DJD) experienced in performing tendinous repair. Following iatrogenic transection, tendons were repaired next to a surgical ruler (Surgical Ruler 160-RL, Covidien, New Jersey) to ensure consistency and precision of suture placement and suture-bite distance among groups. Close apposition of the transected tendons ends was achieved prior to knot-tying without the development of tissue plication at the repair site. A square knot followed by three square throws was used for all repairs, and sutures cut 3 mm from the knot. Randomized testing was completed in three separate sessions, and the results collated.

Group A specimens were repaired using a 3LP pattern as previously described.[14,18] Suture bites were taken at 5, 10, and 15 mm from the repair site, as shown in Figure 1A. Group B specimens were repaired using an exposed double cross-lock pattern (ExDCrL) as shown in Figure 1B. At both the distal and proximal aspects of the tendon, two exposed cross-locks were formed at a width of 3 mm, performed 3 mm apart at a distance of 6 mm from the tenotomy site. The ExDCrL pattern was performed a total three times equidistant from one another around the tendon as shown in Figure 1B. This pattern was modified from those previously described exposed cross-lock patterns used for human zone II repairs.[33] Group C specimens were repaired using an embedded double-cross-lock pattern (EmDCrL), as shown in Figure 1C. At both the distal and proximal aspect of the tendon, two embedded cross-locks were placed at a width of 3 mm, performed 3 mm apart and at a distance of 6 mm from the tenotomy site. The EmDCrL pattern was performed a total three times equidistant from one another around the tendon as shown in Figure 1C. This pattern was modified from the previously described embedded cross-lock patterns for human digital flexor tendon repair.[34] Group D specimens were then repaired using a triple circle-lock patterns (TCiL). At the distal and proximal aspects of the tendon, three circle-locks were formed, using a 2 mm width, performed 3 mm apart at 6 mm away from the tenotomy site. The TCiL pattern was performed a total three times equidistant from one another around the tendon as shown in Figure 1D. The TCiL pattern was modified from previously described circle-lock patterns.[33,35] Finally, Group E specimens were repaired using a Modified Tang (MTang) pattern. This pattern was modified from the previously described Tang pattern.[33,36] The suture was anchored within the proximal aspect of the tendon then passed longitudinally within the tendon, exiting on the lateral aspect of the distal tendon segment. The suture was then passed transversely through the body of the tendon to exit on the contralateral surface. The suture was then passed into the proximal tendon segment at a distance of 15 mm from the repair site. Sutures were then tied on the proximal segment of the tendon. A second suture strand was then inserted into the distal aspect of the tendon and passed longitudinally into the proximal aspect of the tendon and secured with a knot. Last, a third suture was placed in a similar fashion as seen in Figure 1E. All tenorrhaphies except the MTang were performed using 2-0 polypropylene suture (Surgipro, Covidien Ltd., Dublin, Ireland) on a double armed V-20 ½-Circle, 26 mm taper needle. The MTang was performed using 2-0 polypropylene suture (Surgipro, Covidien Ltd.) on a double armed V-20 ½-circle, 26 mm, taper needle with each step repeated using

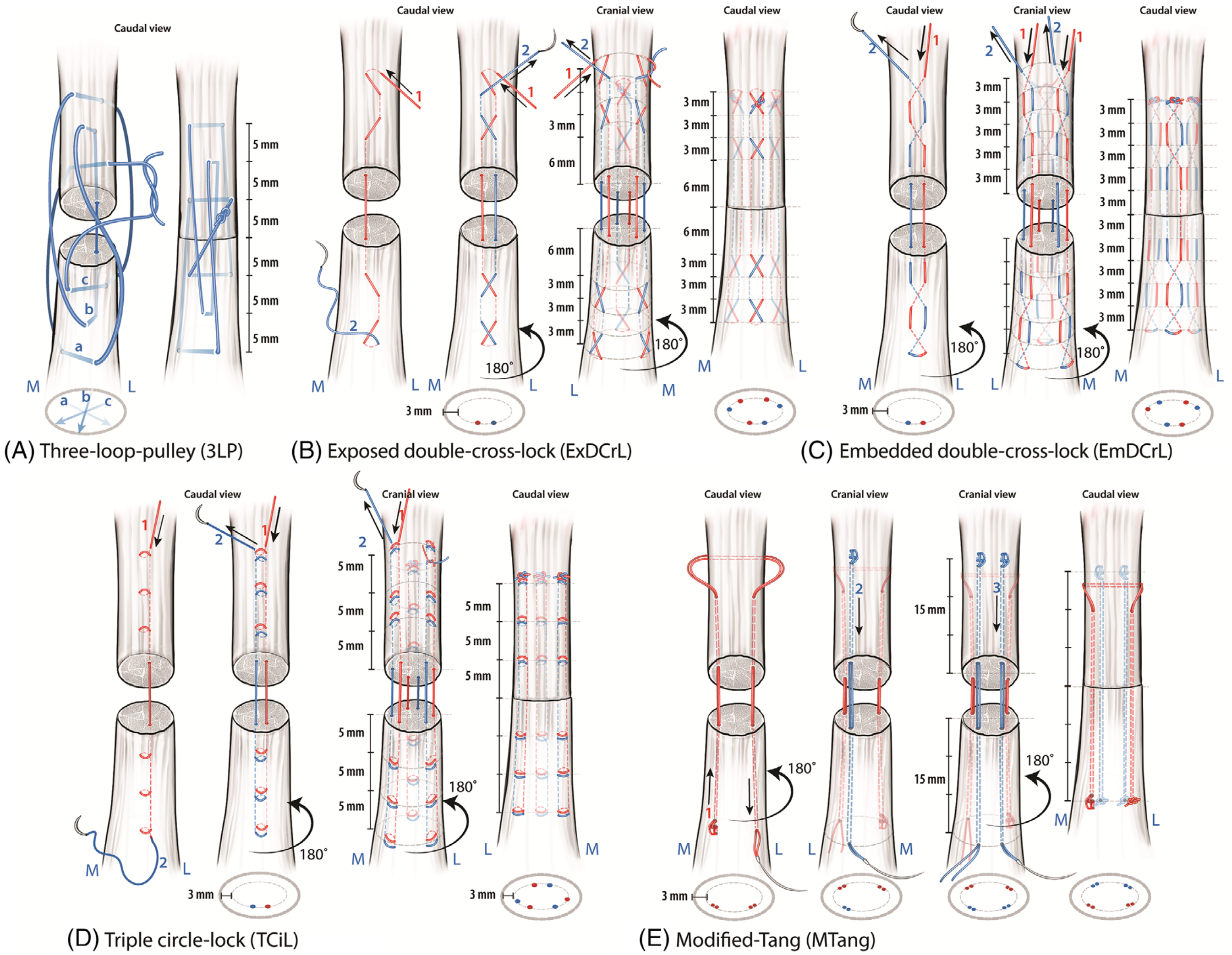

FIGURE 1 Diagram illustrating flexor tendon constructs with the level of tendinous transection shown. Tendons were repaired using: (A) Three-loop-pulley (3LP), (B) Exposed double-cross-lock (ExDCrL), (C) Embedded double-cross-lock (EmDCrL), (D) Triple circle-lock (TCiL), and (E) Modified-Tang (MTang) patterns for suture repair of transected canine tendons. All tenorrhaphies except MTang were performed using 2-0 polypropylene suture (Surgipro, Covidien Ltd.) on a V-20 ½-circle, 26 mm taper needle. The MTang was performed using 2-0 polypropylene suture (Surgipro, Covidien Ltd.) using a double arm V-20 ½-circle, 26 mm, taper needle

the contralateral end of the suture. Suture choice was based on the size of the flexor tendons to ensure it was clinically appropriate for all dogs used in this study. All sutures were within the manufacturer's expiration date with a new suture packet used for each test.

An electromechanical materials testing machine (Model 5944, Instron Inc., Norwood, Massachusetts) was used for tensile testing of all repaired specimens. Transected humeral bone segments were mounted using a 4.8 mm rod placed transversely through the supracondylar foramen that was, in turn, connected to a customized testing jig mounted upon the crosshead of the machine. The manus was secured using a mechanical vice within a modified bone clamp (SKU 1652-1, Sawbones, Vashon Island, Washington). Analysis of gap formation was performed using a computerized software program (ImageJ, National Institute of Health) with video recordings synchronized with the machine load data using an automated triggering system with reference to a millimeter ruler that was axially aligned with the repaired specimens, in the direction of the applied load. A high-speed digital camera (Lumix DMC-FZ200, Panasonic Corporation, Newark, New Jersey) that recorded each test at 100 frames/s was placed at a measured distance of 30 cm from each specimen, level with the tenorrhaphy site. Video data recorded during each test were used to assess for evidence of 1 and 3 mm gap formation that was cross-referenced with the machine load data to determine the load at which both 1 and 3 mm gaps occurred, respectively.

All surgical repairs were mounted within the testing machine and preloaded to 2 N to achieve a consistent resting length and remove slack from specimens. Repaired specimens were then tensioned until failure at a distraction rate of 20 mm/min. Biomechanical data were collected at a frequency of 100 Hz and included assessment of yield, peak, and failure loads (N) and displacement (mm). A digital software program (Matlab R2018b, MathWorks, Natick, Massachusetts) was used to obtain the outcome measures and were evaluated three times by a single investigator (KWC) to ensure accuracy. Yield load was defined as the first identifiable peak followed by a small observable decrease in applied load seen on the load-displacement curve. Peak load was defined as the greatest applied load experienced during each test. Last, failure load was defined as load applied prior to a sudden acute decrease in the load-displacement curve. Method of failure was identified visually at the time of specimen testing and confirmed upon examination of obtained video recordings by a single investigator (KWC). Gap formation was assessed using the minimum distance (mm) between tendon ends to assess for 1 and 3 mm gap formation. A digital caliper calibrated against the ruler of known length observed within video recordings was performed using a computerized program (ImageJ, NIH). Exact time points at which 1 and 3 mm gaps were visualized at the tenorrhaphy site were recorded and cross-referenced with the machine load data.

2.1 | Statistical analysis

Based on a previous study evaluating construct failure loads and a prospective pilot study conducted prior to definitive testing, a sample size of 12 limbs per group provided an 80% power to detect a mean difference in failure load of 40 ± 15 N at a 95% confidence level in independent measures.[27,29]

Data were analyzed using statistical software (JMP v.14.1.0, SAS Institute, Cary, North Carolina). Distribution of data was evaluated for normality using the Shapiro-Wilk test. Parametric and nonparametric variables were compared using a one-way ANOVA and Wilcoxon rank-sum tests, respectively. The Pearson Chi-square test of association was used to compare proportional distributions regarding the modes of construct failure.

3 | RESULTS

There was no difference in the mean tendon CSA between contralateral limbs ($p = .908$) or between experimental groups ($p = .932$). Yield ($p < .0001$), peak ($p < .0001$), and failure loads ($p < .0001$) differed among experimental groups (Table 1). Tendons repaired with ExDCrL, EmDCrL, and MTang increased yield, peak, and failure loads ~2.2x, 2.0x, and 1.9x, respectively, compared to those with 3LP. Constructs repaired with ExDCrL (yield: $p < .0001$; peak: $p < .0001$; failure: $p < .0001$), ExDCrL (yield: $p < .0001$; peak: $p < .0001$; failure: $p < .0001$), EmDCrL (yield: $p < .0001$; peak: $p < .0001$; failure: $p = .0019$), and MTang (yield: $p = .0003$; peak: $p = .0001$; failure: $p = .0304$) loads were higher than those with 3LP. Tendons repaired with TCiL had greater yield ($p = .0314$) and peak loads ($p = .0071$) compared to 3LP, but not failure loads ($p = .3624$). Constructs repaired with ExDCrL had higher yield load ($p = .0034$), peak load ($p = .0061$), and failure load ($p = .0064$) compared to those with TCiL. Tendons repaired with ExDCrL had the greatest yield, peak, and failure loads of all tested specimens.

Load to induce a 1 mm ($p < .0001$) and 3 mm ($p < .0001$) gap differed among experimental groups (Table 2). Tendons repaired with ExDCrL, EmDCrL, and MTang required 1.9x, 1.9x, and 1.6x greater load to create a 3 mm gap, respectively, compared to those with 3LP. Load to create a 1 and 3 mm gap was greater for constructs repaired with ExDCrL (1 mm: $p = .0071$; 3 mm: $p < .0001$), EmDCrL (1 mm: $p = .0004$; 3 mm: $p < .0001$), and MTang (1 mm: $p = .0111$; 3 mm: $p = .0017$) compared to those with 3LP, but not tendons repaired with TCiL (1 mm: $p = .0821$; 3 mm: $p = .8517$). Constructs repaired with ExDCrL required greater applied loads to cause gapping between tendon ends compared to those with TCiL (1 mm: $p < .0001$; 3 mm: $p < .0001$). Tendons repaired with EmDCrL required greater applied loads to cause 3 mm gapping between tendon ends compared

TABLE 1 Mean (±SD) yield, peak, and failure load in Newtons (N) for three-loop pulley (3LP), exposed double-cross-lock (ExDCrL), embedded double-cross-lock (EmDCrL), triple-circle-lock (TCiL), and Modified-Tang patterns (MTang)

Tenorrhaphy pattern	Yield load (N)	Peak load (N)	Failure load (N)
3LP	72.8 ± 6.5[a]	88.3 ± 7.0[a]	86.8 ± 6.9 [a]
ExDCrL	173.0 ± 8.9[c]	181.0 ± 8.4[c]	179.9 ± 8.3[c]
EmDCrL	156.8 ± 10.4[b]	161.7 ± 9.1[c]	161.1 ± 9.1[c]
TCiL	117.7 ± 12.3[b]	134.8 ± 9.2[b]	132.9 ± 9.5[b]
MTang	138.3 ± 11.9[b]	148.4 ± 10.7[b]	147.2 ± 10.5[b]

Note: Superscripts of different letters denote differences between groups ($p < .0001$).

TABLE 2 Table showing the mean (±SD) load in Newtons (N) for three-loop pulley (3LP), exposed double-cross-lock (ExDCrL), embedded double-cross-lock (EmDCrL), triple-circle-lock (TCiL), and Modified-Tang patterns (MTang) required to create 1 and 3 mm gap formation between tendon ends

Tenorrhaphy pattern	Load (N) to 1 mm gapping	Load (N) to 3 mm gapping
3LP	64.3 ± 6.4[a]	70.9 ± 6.9 [a]
ExDCrL	105.3 ± 6.5[b]	131.5 ± 7.7 [c]
EmDCrL	119 ± 10.3 [b]	133.6 ± 11.7 [c]
TCiL	33.3 ± 4.4 [b]	59.2 ± 6.6 [b]
MTang	101.8 ± 10.3 [a]	116.2 ± 7.4 [a]

Note: Superscripts of different letters denote differences between groups ($p < .0001$).

to those with TiCL (EmDCrL: $p < .0001$; MTang: $p < .0001$).

Mode of specimen failure differed between experimental groups ($p < .0001$). Tendons repaired with EmDCrL ($n = 11/12$; 92%), ExDCrL ($n = 12/12$; 100%), and TCiL ($n = 12/12$; 100%) failed predominantly by suture breakage. Half of constructs repaired with MTang specimens failed by suture breakage ($n = 6/12$; 50%), compared to those with 3LP that failed predominantly due to suture pull-through ($n = 10/12$; 83%).

4 | DISCUSSION

In this study, we evaluated the effect of four novel tenorrhaphy patterns for their biomechanical and gapping characteristics of experimentally repaired canine flexor tendon constructs. In agreement with our hypothesis, tendons repaired with novel patterns ExDCrL, EmDCrL, and MTang increased yield, peak, and failure loads (~2.2x, 2.0x, and 1.9x, respectively) compared to those with 3LP. Constructs repaired with ExDCrL, EmDCrL, and MTang required a greater load to cause a 1 mm gap (~1.6x, 1.9x, and 1.6x, respectively) and a 3 mm gap (~1.9x, 1.9x, and 1.6x, respectively) between tendon ends compared to those with 3LP. Tendons repaired with ExDCrL were superior compared to those with TCiL; however, constructs repaired with TCiL had better yield and peak loads compared to those with 3LP.

In this study, constructs repaired with ExDCrL pattern had the greatest yield, peak, and failure loads, whereas those repaired with EmDCrL suture pattern were the most resistant in preventing 1 and 3 mm gap formation at the tenorrhaphy site. Our study is the first to report the effectiveness of tendons repaired with cross-lock patterns in comparison to those with a 3LP pattern with respect to assessed biomechanical loads and development of gap formation. The locking nature of the ExDCrL, EmDCrL, and MTang patterns incorporate a greater number of collagen fibrils and "locked-repairs" have been shown to be superior to nonlocking patterns in cadaveric human and canine translational models.[21,35,37–39] For nonlocking patterns, suture passes loop through the core of the tendon substance but do not tighten and constrict around the collagen fibers themselves as locking patterns do.[40] Lin et al. showed that in humans, tendons repaired with "locking" repairs led to a 3.77x and 1.68x greater tensile failure strength and 1.73x and 1.26x greater stiffness compared to those with simple circumferential and Lembert running sutures, respectively.[41] The number of "locking-zones" has also been shown to affect repair site strength.[42] For this reason, suture pattern configurations utilized in our study were specifically controlled to minimize sample variation among tested specimens. The biomechanical strength of constructs repaired with two locking patterns, the 10-strand cross-lock pattern and Lin-locking pattern were recently evaluated and compared to those with 3LP in an equine ex vivo model by Smith et al.[43] In this aforementioned study, investigators showed that tendons repaired with 10-strand cross-locked pattern was superior to those with 3LP regarding failure loads and gap formation at failure.[43] It should be noted that in this study, yield and peak loads, and loads to cause gap formation were not examined.[43] Since increasing the number of strands crossing the repair has been positively correlated with repair site strength,[30] their results may be inherently biased. In our study, both ExDCrL and 3LP had six-strands traversing the tenotomy site. We demonstrated that that tendons repaired with ExDCrL were stronger than 3LP and TCiL. We hypothesize these observed findings relate to the suture patterns, as other extraneous confounding variables; tendon type, bite distance from the transection site,[44] suture material,[45] and suture size[46] which affects construct strength were controlled during testing.

Similar to previous biomechanical studies, there was no difference in examined loads found between constructs repaired with ExDCrL, EmDCrL, and MTang suture patterns.[30] Tendons repaired with MTang has greater yield, peak, and failure loads and loads at 1 and 3 mm gap formation compared to those with 3LP. It should be noted that no prior studies to date have evaluated constructs repaired with MTang compared to those with 3LP. Xie et al. compared the biomechanical strength of tendons repaired with original Tang pattern against those with a single-exposed cross lock pattern.[36] Their results indicated that peak loads of constructs repaired with Tang sutures were no different from those with a single-exposed cross-lock pattern, which is in agreement with the results of our study.[36] However, Xie et al. examined loads at 2 mm gap formation of tendons repaired with Tang suture and found them to be greater than those with the single-exposed cross-lock pattern.[36] It should be noted that the original Tang suture pattern and single-exposed cross lock patterns utilized in a study by Xie et al.[36] have multiple key differences compared to the MTang and ExDCrL patterns used in our study. The original pattern used three longitudinal sutured components crossing the repair site.[47] In the study presented here, the MTang pattern was created by adding a transverse component to the two longitudinal looped suture configuration placed within the tendinous core, in attempts to improve the overall suture-tissue interaction and increase the strength and resistance to construct deformation. Wang et al. studied the biomechanical differences between constructs repaired with original Tang and those with the modified Tang suture patterns using linear and 90° angular loading protocols. In this study, modified Tang patterns utilized a single longitudinal looped component that interacted with the tendon substance compared to two loops used in their study.[48] Wang et al. showed that loads to cause gap formation and peak loads of tendons repaired with Tang were not different from those with modified Tang pattern under ex vivo conditions of linear loading.[48] However, peak loads of tendons repaired with modified Tang were greater under angular tension. Since the major difference between the Tang and modified Tang pattern was the transverse component, Wang et al. proposed that the transverse component may have led to the improvements in ultimate construct strength.[48] For this reason, the transverse component of the modified Tang was utilized in the MTang pattern described in this study.

In our study, constructs repaired with TCiL required similar loads to cause both 1 and 3 mm gaps respectively compared to those with 3LP. Moreover, lower loads to cause both 1 and 3 mm gaps were seen in tendons repaired with TCiL groups compared to those with ExDCrL, EmDCrL, and MTang repairs. To date, no studies have compared constructs repaired with TCiL to those with 3LP or described the use of TCiL within the human or veterinary literature. To the authors knowledge, only tendons repaired with a single circle-lock pattern has been evaluated.[33,35,49] In a study by Croog et al., they compared load application required to cause 2 mm gap formation and peak loads of a single exposed cross-lock construct and a simple lock construct to a single circle-lock pattern placed within the core of the tendon to two single cross-lock pattern construct and a modified LL pattern construct.[49] They showed that tendons repaired with single cross-lock was stronger than both the single circle-lock and modified LL patterns, respectively.[49] In contrast, a study by Xie and Tang demonstrated contradicting results.[33] They compared the strength of tendons repaired with single circle-lock, single embedded cross-lock and single exposed cross-lock suture patterns in porcine flexor profundus tendons.[33] The load to cause 2 mm gapping, and peak loads were assessed.[33] No differences were found between tendons repaired with the patterns listed above,[33] which differs from the results from the Croog et al.[49] and our study, respectively. Based upon the findings of Xie et al.,[23] the locking diameter that was chosen (2 mm) for this study was deemed to be appropriate. Xie et al. evaluated the biomechanical effects of constructs repaired with a single circle-lock pattern using different lock diameters (1, 2, and 3 mm). They showed an increase in construct strength from 1 to 2 mm, however, no difference between 2 and 3 mm.[23] The only difference in suture configuration between Xie et al. and the study presented here is the number of circle locks used for pattern completion. Therefore, it is plausible that the increasing the number of circle-locks of the TCiL pattern may affect construct strength and is an area for future focused exploration.

Similar to previous studies, tendons repaired with the novel patterns presented here were more likely to fail by suture breakage compared to suture pull-through as seen in tendons repaired with 3LP, suggesting better stress distribution throughout the construct.[45,50] All constructs repaired with ExDCrL and TCiL and 92% using EmDCrL suture patterns failed by suture breakage. Suture failure suggests the suture itself was the weakest component of the repair. Lawrence et al. assessed the biomechanics of tendons repaired with single exposed cross-lock repair using various suture materials in a porcine model.[45] They found that all constructs repaired with single exposed cross-locked repairs failed due to suture rupture,[45] similar to the results of our study. In contrast, tendons repaired with 3LP predominantly failed due to suture pull-through. Our results were similar to previous veterinary studies.[31,50] Putterman et al. evaluated tendons repaired with core 3LP with and without epitendinous suture augmentation and observed that pull-through was the most common failure mode in tendons repaired with 3LP.[50] It is plausible that if a larger suture was used for tenorrhaphy that different results may have been obtained.[46]

The clinical application of these novel patterns in dogs requires further in vivo evaluation. Factors that were not examined as part of this experimental design include the effect of these novel patterns on the local tendinous blood supply. However, in human hand surgery, locking patterns are widely utilized and recommended for use in clinical patients. Osada et al. used a modified MTang pattern, on a total of 27 fingers with zone II flexor tendon injuries.[51] Most patients (97%) had a good to excellent outcome with at least 13-month follow-up, with all patients able to start early unassisted active flexion 1 day following acute surgical intervention.[51] Since human studies have had success with application of similar locking patterns with favorable results, use of ExDCrL, EmDCrL, and MTang are supportive for further in vivo evaluation. The SDFT of the dog has also been widely utilized as a translational model due to homology and size compared to human tendons, which highlights the importance of this field of research.[26,27,33,41,52]

There are some appreciable limitations related to the ex vivo nature of this study. Incised cadaveric tendons are inherently different from those seen clinically affected by chronic degenerative disease. In addition, cyclical loading may have better mimicked in vivo load application seen in dogs.[53] Tensioning of sutures was not standardized which have led to minor degrees of variability among repaired specimens. Last, it may be clinically challenging to perform these patterns depending on the size and length of the proximal and distal tendon segments.

In conclusion, tendons repaired with the novel patterns, ExDCrL, EmDCrL, and MTang, had greater yield, peak, and failure loads as well as loads to cause both 1 and 3 mm gap formation compared to 3LP. These novel suture patterns failed by suture breakage. Tendons repaired with ExDCrL, EmDCrL, or MTang suture patterns therefore increased tenorrhaphy strength and decreased the occurrence of gap formation. Further clinical studies are warranted to determine the effectiveness and practicality of these novel suture patterns in the Dogs.

ACKNOWLEDGMENTS

All surgical sutures used for the purpose of this study were kindly donated by Medtronic, Inc., Mansfield, MA. Medtronic played no role in the study design and methodology, data analysis, decision to publish, or preparation of the resultant manuscript. The authors received funding from the Firestone Canine Research Endowment, Department of Clinical Science, College of Veterinary Medicine, North Carolina State University, and the Wade O. Brinker Research Award from the Veterinary Orthopedic Society.

CONFLICT OF INTEREST

The authors declare no conflicts of interest or disclosures to report.

AUTHOR CONTRIBUTIONS

King Wa Chiu: contributions include performance of all suture repairs, construct testing, analysis of biomechanical and gapping data, interpretation of data, writing and drafting of the work, revision of the work, and final approval of the submitted manuscript. Daniel J. Duffy: contributions include design of the study and methodology performed, oversight of suture repairs, construct testing, analysis of biomechanical and gapping data, interpretation of data, assistance in writing and drafting of the work, revision of the work, and final approval of the submitted manuscript. Yi-Jen Chang: contributions include assistance with cadaveric collection, biomechanical testing, interpretation of data, and final approval of the submitted manuscript. Lewis Gaffney: contributions include assistance with biomechanical testing, interpretation of data, and final approval of the submitted manuscript. Matthew B. Fisher: assistance during biomechanical testing, review of data collected, and final approval of the submitted manuscript.

ORCID

Daniel J. Duffy https://orcid.org/0000-0002-3043-8877

REFERENCES

1. Duffy DJ, Main RP, Moore GE, Breur GJ, Millard RP. Ex vivo biomechanical comparison of barbed suture and standard polypropylene suture for acute tendon laceration in a canine model. *Vet Comp Orthop Traumatol*. 2015;28:263-269.
2. Hill JR, Eekhoff JD, Brophy RH, Lake SP. Elastic fibers in orthopedics: form and function in tendons and ligaments, clinical implications, and future directions. *J Orthop Res*. 2020;38:2305-2317.
3. Dueland R, Quenin J. Triceps tenotomy: biomechanical assessment of healing strength [dogs]. *J Am Anim Hosp Assoc*. 1980;16:507-512.
4. Dy CJ, Hernandez-Soria A, Ma Y, et al. Complications after flexor tendon repair: a systematic review and meta-analysis. *J Hand Surg Am*. 2012;37:543-551.
5. Hoffmann A, Gross G. Tendon and ligament engineering: from cell biology to in vivo application. *Regen Med*. 2006;1:563-574.
6. Gelberman RH, Woo SL, Lothringer K, et al. Effects of early intermittent passive mobilization on healing canine flexor tendons. *J Hand Surg Am*. 1982;7:170-175.
7. Guerin S, Burbidge H, Firth E, et al. Achilles tenorrhaphy in five dogs: a modified surgical technique and evaluation of a cranial half cast. *Vet Comp Orthop Traumatol*. 1998;11:205-210.
8. Morshead D, Leeds EB. Kirschner-Ehmer apparatus immobilization following Achilles tendon repair in six dogs. *Vet Surg*. 1984;13:11-14.
9. de Haan J, Goring R, Renberg C, et al. Modified transarticular external skeletal fixation for support of Achilles tenorrhaphy in four dogs. *Vet Comp Orthop Traumatol*. 1995;8:32-35.
10. Norton J, DeCamp C, Yu J, et al. Use of a single-ring transarticular fixator construct for immobilisation of the talocrural joint following common calcaneal tenorrhaphy. *Vet Comp Orthop Traumatol*. 2009;22:430-435.
11. Sivacolundhu R, Marchevsky A, Read R, et al. Achilles mechanism reconstruction in four dogs Murdoch University

Veterinary Hospital, Murdoch, WA, Australia. *Vet Comp Orthop Traumatol*. 2001;14:25-31.
12. Nielsen C, Pluhar G. Outcome following surgical repair of achilles tendon rupture and comparison between postoperative tibiotarsal immobilization methods in dogs. *Vet Comp Orthop Traumatol*. 2006;19:246-249.
13. Pettengill KM. The evolution of early mobilization of the repaired flexor tendon. *J Hand Ther*. 2005;18:157-168.
14. Berg RJ, Egger EL. In vitro comparison of the three loop pulley and locking loop suture patterns for repair of canine weightbearing tendons and collateral ligaments. *Vet Surg*. 1986;15:107-110.
15. Gall TT, Santoni BG, Egger EL, et al. In vitro biomechanical comparison of polypropylene mesh, modified three-loop pulley suture pattern, and a combination for repair of distal canine achilles' tendon injuries. *Vet Surg*. 2009;38:845-851.
16. Krackow KA, Thomas SC, Jones LC. A new stitch for ligament-tendon fixation. Brief note. *J Bone Joint Surg Am*. 1986;68:764-766.
17. Montgomery RD, Barnes SL, Wenzel JGW, et al. In-vitro comparison of the Krackow and locking loop suture patterns for tenorrhaphy of flat tendons. *Vet Comp Orthop Traumatol*. 1994;7:31-34.
18. Moores AP, Owen MR, Tarlton JF. The three-loop pulley suture versus two locking-loop sutures for the repair of canine achilles tendons. *Vet Surg*. 2004;33:131-137.
19. Pjanowski GJ, Stein LE, Turner TA. Strength characteristics and failure modes of suture patterns in severed goat tendons. *Vet Surg*. 1989;18:335-339.
20. Renberg W, Radlinsky M. In vitro comparison of the locking loop and continuous cruciate suture patterns. *Vet Comp Orthop Traumatol*. 2001;14:15-18.
21. Hotokezaka S, Manske PR. Differences between locking loops and grasping loops: effects on 2-strand core suture. *J Hand Surg Am*. 1997;22:995-1003.
22. Krackow KA, Thomas SC, Jones LC. Ligament-tendon fixation: analysis of a new stitch and comparison with standard techniques. *Orthopedics*. 1988;11:909-917.
23. Xie RG, Xue HG, Gu JH, et al. Effects of locking area on strength of 2- and 4-strand locking tendon repairs. *J Hand Surg Am*. 2005;30:455-460.
24. Tang JB. *Tendon Surgery of the Hand*. 1st ed. Philadelphia, PA: Saunders; 2012.
25. Worth A, Danielsson F, Bray J, Burbidge HM, Bruce WJ. Ability to work and owner satisfaction following surgical repair of common calcanean tendon injuries in working dogs in New Zealand. *N Z Vet J*. 2004;52:109-116.
26. Gelberman RH, Boyer MI, Brodt MD, et al. The effect of gap formation at the repair site on the strength and excursion of intrasynovial flexor tendons. *J Bone Joint Surg Am*. 1999;81:975-982.
27. Aoki M, Pruitt D, Kubota H, et al. Effect of suture knots on tensile strength of repaired canine flexor tendons. *J Hand Surg Am*. 1995;20:72-75.
28. Greenwald DP, Randolph MA, Hong H-Z, May JW Jr. Augmented Becker versus modified Kessler tenorrhaphy in monkeys: dynamic mechanical analysis. *J Hand Surg Am*. 1995;20:267-272.
29. Thurman RT, Trumble TE, Hanel DP, et al. Two-, four-, and six-strand zone II flexor tendon repairs: an in situ biomechanical comparison using a cadaver model. *J Hand Surg Am*. 1998;23:261-265.
30. Wu YF, Tang JB. Recent developments in flexor tendon repair techniques and factors influencing strength of the tendon repair. *J Hand Surg Eur Vol*. 2014;39:6-19.
31. Cocca CJ, Duffy DJ, Kersh ME, Kim W, Groenewold A, Moore GE. Biomechanical comparison of three epitendinous suture patterns as adjuncts to a core locking loop suture for repair of canine flexor tendon injuries. *Vet Surg*. 2019;48:1245-1252.
32. Goh K, Chen Y, Chou S, et al. Effects of frozen storage temperature on the elasticity of tendons from a small murine model. *Animal*. 2010;4:1613-1617.
33. Xie RG, Tang JB. Investigation of locking configurations for tendon repair. *J Hand Surg Am*. 2005;30:461-465.
34. Savage R, Risitano G. Flexor tendon repair using a "six strand" method of repair and early active mobilisation. *J Hand Surg Br*. 1989;14:396-399.
35. Tang JB, Tan J, Xu Y. Lengthening and locking: two ways to improve repair strength of obliquely lacerated tendons. *J Hand Surg Am*. 2003;28:832-837.
36. Xie RG, Zhang S, Tang JB, Chen F. Biomechanical studies of 3 different 6-strand flexor tendon repair techniques. *J Hand Surg Am*. 2002;27:621-627.
37. Hatanaka H, Zhang J, Manske PR. An in vivo study of locking and grasping techniques using a passive mobilization protocol in experimental animals. *J Hand Surg Am*. 2000;25:260-269.
38. Wada A, Kubota H, Hatanaka H, et al. The mechanical properties of locking and grasping suture loop configurations in four-strand core suture techniques. *J Hand Surg Br*. 2000;25:548-551.
39. Tanaka T, Amadio PC, Zhao C, Zobitz ME, Yang C, An KN. Gliding characteristics and gap formation for locking and grasping tendon repairs: a biomechanical study in a human cadaver model. *J Hand Surg Am*. 2004;29:6-14.
40. Pennington DG. The locking loop tendon suture. *Plast Reconstr Surg*. 1979;63:648-652.
41. Lin GT, An KN, Amadio PC, Cooney WP III. Biomechanical studies of running suture for flexor tendon repair in dogs. *J Hand Surg Am*. 1988;13:553-558.
42. Dona E, Gianoutsos MP, Walsh WR. Optimizing biomechanical performance of the 4-strand cruciate flexor tendon repair. *J Hand Surg Am*. 2004;29:571-580.
43. Smith RL, Murphy DJ, Day RE, Lester GD. An ex vivo biomechanical study comparing strength characteristics of a new technique with the three-loop pulley for equine tenorrhaphy. *Vet Surg*. 2011;40:768-773.
44. Duffy DJ, Cocca CJ, Kersh ME, Kim W, Moore GE. Effect of bite distance of an epitendinous suture from the repair site on the tensile strength of canine tendon constructs. *Am J Vet Res*. 2019;80:1034-1042.
45. Lawrence TM, Davis TR. A biomechanical analysis of suture materials and their influence on a four-strand flexor tendon repair. *J Hand Surg Am*. 2005;30:836-841.
46. Duffy DJ, Curcillo CJ, Chang Y-J, Moore GE. Effect of suture caliber on the tensile strength of tenorrhaphies in cadaveric canine tendons. *Am J Vet Res*. 2020;81:714-719.
47. Tang J, Shi D, Gu Y, et al. Double and multiple looped suture tendon repair. *J Hand Surg Br*. 1994;19:699-703.

48. Wang B, Xie R, Tang J. Biomechanical analysis of a modification of Tang method of tendon repair. *J Hand Surg Br*. 2003;28:347-350.
49. Croog A, Goldstein R, Nasser P, Lee SK. Comparative biomechanic performances of locked cruciate four-strand flexor tendon repairs in an ex vivo porcine model. *J Hand Surg Am*. 2007;32:225-232.
50. Putterman AB, Duffy DJ, Kersh ME, Rahman H, Moore GE. Effect of a continuous epitendinous suture as adjunct to three-loop pulley and locking-loop patterns for flexor tendon repair in a canine model. *Vet Surg*. 2019;48:1229-1236.
51. Osada D, Fujita S, Tamai K, Yamaguchi T, Iwamoto A, Saotome K. Flexor tendon repair in zone II with 6-strand techniques and early active mobilization. *J Hand Surg Am*. 2006;31:987-992.
52. Zhao C, Amadio PC, Paillard P, et al. Digital resistance and tendon strength during the first week after flexor digitorum profundus tendon repair in a canine model in vivo. *J Bone Joint Surg Am*. 2004;86:320-327.
53. Pruitt DL, Manske PR, Fink B. Cyclic stress analysis of flexor tendon repair. *J Hand Surg Am*. 1991;16:701-707.

How to cite this article: Chiu KW, Duffy DJ, Chang Y-J, Gaffney L, Fisher MB. Ex vivo evaluation of novel core tenorrhaphy patterns in dogs. *Veterinary Surgery*. 2021;50(6):1316-1325. https://doi.org/10.1111/vsu.13678