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EXPERIMENTAL LAB RESEARCH

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Biomechanical evaluation of three adjunctive methods of orthopedic tension band-wire fixation to augment simulated patella tendon repairs in dogs

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Abstract

Objective: To evaluate the effects of three adjunctive methods of tension band wire fixation (TBWF) on the biomechanical properties, gap formation, and failure mode in simulated canine patella tendon rupture (RPT).

Study design: Randomized, ex vivo.

Sample population: Paired hindlimbs from 32 dog cadavers.

Methods: Patellar tendons (PTs) and associated bone-muscle-tendon units were harvested. Each PT was transected then sutured using a core locking loop and simple continuous epitendinous pattern. Each hindlimb was randomly assigned to one of three groups ($n = 18$ hindlimbs/group) using 18 gauge 316 L wire, anchored to the tibial crest distally, to perform transpatellar, suprapatellar, or combined tension band-wire (TBW) augmentation. Ten hindlimbs were utilized as control specimens. Yield, peak, and failure loads, stiffness, loads to 1 and 3 mm gap formation, and failure mode were evaluated.

Results: Combined transpatellar and suprapatellar TBW augmentation was superior to transpatellar or suprapatellar groups alone. Yield ($p = .0008$), peak ($p = .004$), and failure loads ($p = .005$) were greater for the combined group than for the transpatellar ($p = .048$) and suprapatellar groups ($p = .01$) respectively. There was no difference regarding the occurrence of 1 or 3 mm gap formation (1 mm, $p = .05$; 3 mm, $p = .06$); however, loads required to cause gap formation were greater in the combined group ($p = .036$). Mode of failure differed between techniques used for PT augmentation ($p < .001$).

Abbreviations: CSA, cross-sectional area; LD, load displacement; LL, locking loop; N, newtons; PT, patellar tendon; PTs, patellar tendons; RPT, patellar tendon rupture; SCES, simple continuous epitendinous suture; TBW, tension band wire; TBFW, tension band wire fixation; 3LP, three-loop pulley.

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Conclusion: Combined transpatellar and suprapatellar adjunctive TBW augmentation for simulated PT repairs was biomechanically superior to either transpatellar or suprapatellar TBWF alone.

Clinical significance: Combined suprapatellar and transpatellar TBWF may offer a viable surgical option for increased repair-site strength and greater loads to gap formation. Further studies investigating alternative techniques and materials for RPT repair augmentation are warranted.

1 | INTRODUCTION

The patellar tendon (PT) is the tendinous insertion of the quadriceps femoris muscle extending from the patella sesamoid to the tibial tuberosity, which functions to facilitate femorotibial extension and both stifle and patella stabilization.[1,2] In dogs, rupture of the patellar tendon (RPT) is an infrequently reported injury caused by direct laceration and trauma, or secondary to forceful simultaneous stifle flexion and quadriceps femoris muscle contraction.[1,3,4] However, endocrine disorders and collagenous connective tissue abnormalities have been described.[1,5–7] In humans, RPT has been reported due to systemic inflammatory disorders or corticosteroid-associated tendinous deterioration.[5,7]

Current techniques for the repair of RPT in dogs include primary tendinous repair using core suture patterns, including the locking loop (LL), three-loop pulley (3LP), Bunnell–Mayer, mattress suture, Krackow, and various repair modifications.[6,8–12] Previous reports support the use of concurrent augmentation of primary tenorrhaphy techniques using adjunctive stabilization procedures to reduce the risk of repair failure and to counteract the considerable forces applied to the PT during active quadriceps contraction.[1,4,7,13,14] Use of transpatellar or suprapatellar (also known as circumpatellar) augmentation using monofilament nylon or 316 L stainless steel wire has been described.[1,3–7,14] Distally, orthopedic wire is anchored through the tibial tuberosity using transosseous tunnels and functions as an internal splint to aid in the apposition of tendon ends prior to primary repair, and subsequently provide secondary dynamic stabilization to the tendinous anastomosis.[1,3–7,14] Use of autogenous fascia lata grafts,[1,13,15,16] and PT plating has been described.[1] Further stifle stabilization using either external coaptation[3,5] or transarticular external skeletal fixation[3–5,7] has also been advocated by surgeons to further promote postoperative joint immobilization and reduce tensile loads placed directly on the repair.

Current methods of RPT repair protection are problematic for several reasons. Use of external coaptation for immobilizing the stifle joint postoperatively may aid in protecting the primary repair; however, soft-tissue morbidity has been reported in 63% of dogs.[4,8,17] Most notably, concerns exist regarding failure of the primary tenorrhaphy, resulting in the need for either revision surgery or secondary intervention.[4,5] Postulated reasons for RPT repair failure relate to the initial strength of primary repair, with several studies focused on optimization of suture repair techniques.[6,11] In a study by Biskup et al. the biomechanical properties of cadaveric canine patella-tibia-ligament segments were evaluated.[18] Failure loads for tested segments ranged from 811 to 3451 N depending on the size of the dogs used.[18] A common sequela to using either transpatellar or suprapatellar tension band wire (TBW) includes the need for implant removal postoperatively due to subsequent lameness, seroma formation, or excoriation of overlying soft tissues due to wire breakage.[3,4,15] Given that TBW augmentation following RPT repair is a widely adopted practice among surgeons, there is a paucity of information within the veterinary literature to support a superior method for wire placement.[4,11] This information is of use to veterinary surgeons in efforts to reduce the occurrence of repair failures and increase the tensile strength of RPT repairs.

Although use of transpatellar and suprapatellar TBW have been reported following RPT repair within the veterinary literature,[1,3–7,14] there are infrequent reports of the combined use of transpatellar and suprapatellar wire-fixation techniques,[4,13] and biochemical testing focused on these methods of augmentation is warranted.

The objective of this study was to evaluate the effect of three different techniques for TBW augmentation following primary PT repair using 316 L 18 gauge orthopedic wire (transpatellar, suprapatellar, or combined transpatellar and suprapatellar) on the biomechanical properties and failure mode in a canine RPT model. Our hypothesis was that the use of combined transpatellar and suprapatellar TBW augmentation would be biochemically superior, exhibiting greater yield, peak, and failure loads than other techniques. Our secondary hypothesis was that there would be no difference in failure mode or gap formation among groups.

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2 | MATERIALS AND METHODS

2.1 | Specimen processing and preparation

Prior to collection, a board-certified surgeon (Daniel J. Duffy) performed a focused orthopedic examination and confirmed lack of visible abnormalities on paired canine hindlimbs. Hindlimbs were harvested from 32 healthy, mixed-breed adult dogs immediately following euthanasia at a local animal shelter. Dogs were euthanized for reasons unrelated to this study using sodium pentobarbital (dose: 1 mL/5 kg bodyweight). Prior medical history was available but patient demographics, including patient sex and weight, were not reported. Given the secondary use of specimens, an institutional animal care and use committee approval was not required by North Carolina State University Veterinary Teaching Hospital, Department of Clinical Sciences. Patients were excluded if they had a history of orthopedic disease, angular limb deformity, endocrine disorders, or were receiving any medications within 1 month of collection.

In each respective hindlimb, the patella and its associated bone-muscle-tendon unit were dissected manually. Soft tissues were removed using a combination of blunt and sharp dissection. The distal part of the quadriceps femoris muscles, patella and parapatellar fibrocartilages, PT, tibial tuberosity with each corresponding tibia were preserved as the construct to be repaired and tested. The quadriceps femoris muscles were transected at a measured distance of 4 cm proximal to the proximal pole of the patella at the musculotendinous junction to aid with specimen fixation. Distally, respective tibiae were disarticulated at the tibiotarsal joint by transection of the joint capsule and supporting collateral ligaments. All other tissues were removed and discarded. Saline (0.9% NaCl) was used during harvest and dissection to keep specimens moist and prevent desiccation using a spray bottle. After collection, each specimen was labeled, wrapped in saline-soaked gauze, and stored in a thermostatically controlled environment at −20°C using a validated technique in impervious bags.[19] Prior to tenotomy, repair and biochemical testing, specimens were thawed at room temperature (21°C) for 12 h.[20]

2.2 | Treatment groups

Prior to tenotomy and surgical repair, each hindlimb was randomly assigned to one of three treatment groups ($n = 18$ hindlimbs/group; 54 specimens total). A fourth group ($n = 10$ hindlimbs), composed of untenotomized specimens, was used to assess and validate test methodology and serve as a control group representing strength and failure mode of native tissues. Hindlimb specimens originating from the same cadaver were controlled from being placed within the same group.

On the day of testing, the PT was further dissected using a #15 Bard-Parker scalpel blade if any residual joint capsule and patella bursal attachments were present. Respective PTs were then uniformly transected on a flat and durable surface to provide retropatellar pressure and allow for a standardized tenotomy using a #10 scalpel blade across the midbody of the PT, at a measured distance of 20 mm from the enthesis of the PT on the tibial tuberosity. All surgical repairs were performed by a board-certified small-animal surgeon (Daniel J. Duffy) experienced in tendon repairs both in clinical and research settings. Following tenotomy, photographic images were obtained of the distal cut surface of each PT immediately adjacent and parallel to a calibrated millimeter ruler (iPhone XR; Apple, Cupertino, California) at a distance of 10 cm. A single trained investigator (Yi-Jen Chang) measured the cross-sectional area (CSA) of each distal PT stump three times using computerized software (Image J, National Institutes of Health, Bethesda, Maryland) from which the mean CSA was calculated.

Primary tenorrhaphy was performed in all tenotomized specimens using a core LL suture technique using 2–0 polypropylene suture (Surgipro; Covidien Ltd, Dublin, Ireland), as described previously (Figure 1A).[21–24] A suture was first passed through the proximal tendon end transversely 1 cm from the transected end, a longitudinal bite was then taken 1.5 cm from the same severed proximal tendon end, and finally a suture was passed from the upper surface 1 cm from the severed end in a longitudinal direction across the gap, through the tendon, and repeated within the distal tendon end.[24] A simple continuous epitendinous suture (SCES) was performed using a continuous circumferential pattern with 3–0 polypropylene suture (Surgipro; Covidien Ltd, Dublin, Ireland) with bites placed 2 mm apart and 5 mm from the transected tendon ends.[23,24] Both core and epitendinous patterns were tightened to achieve close apposition of tendon ends, then secured with a square knot followed by three throws; a suture was then cut 3 mm from the knot. Suture size was elected based upon prior published research,[25,26] used in adherence with the manufacturer's guidelines.

Following completion of the primary tenorrhaphy, repairs were then randomized (https://www.randomizer.org; Lancaster, Pennsylvania) to receive one of three different augmentation techniques using 18 gauge 316 L veterinary orthopedic wire (Imex, Longview, Texas) as described with either a transpatellar, suprapatellar, or

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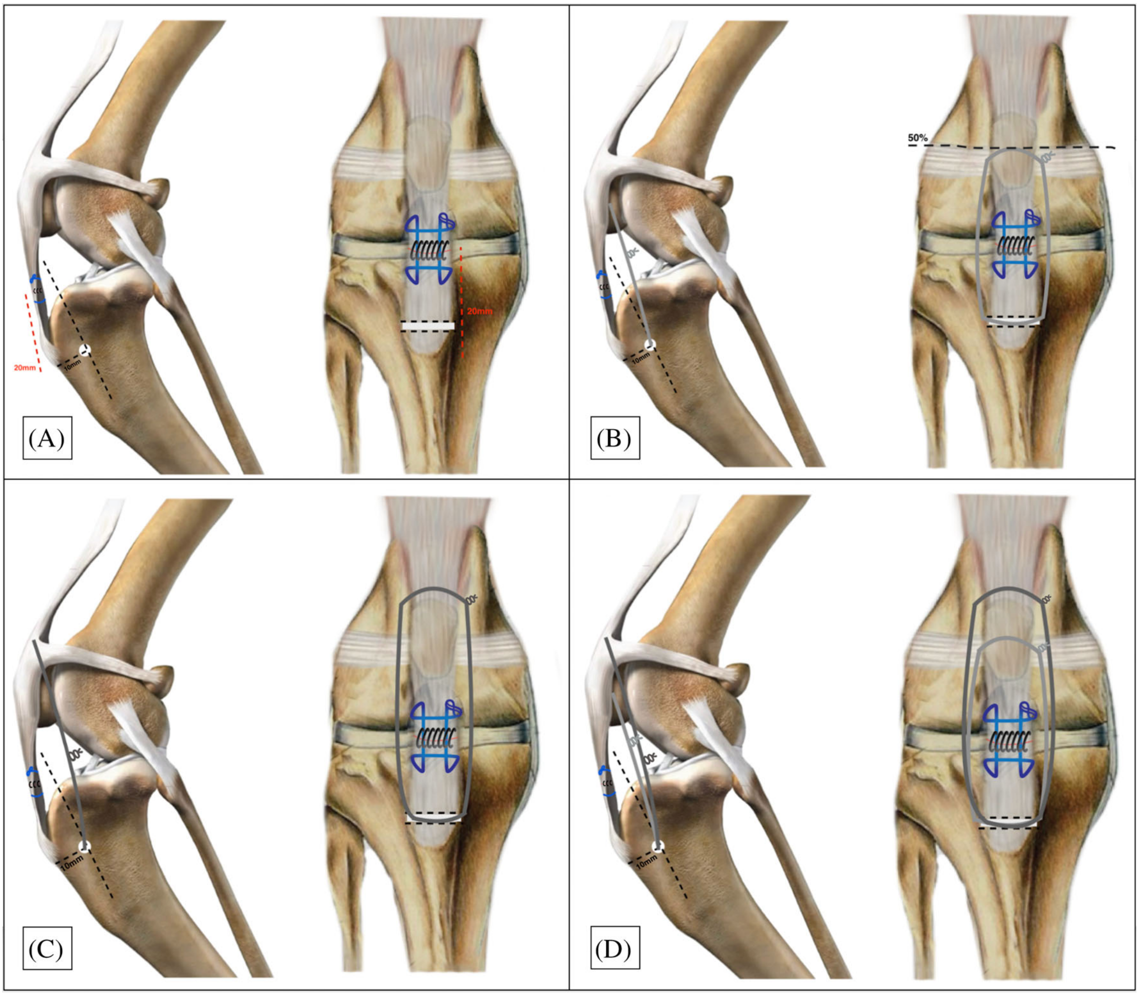

FIGURE 1 Lateral and craniocaudal images showing (A) The patella tendon (PT) following sharp tenotomy and tenorrhaphy using a core locking-loop pattern and simple continuous epitendinous suture (SCES) at a measured distance of 20 mm from the enthesis of the PT on the tibial tuberosity. The location of the mediolateral hole in the cranioproximal tibia can be seen at a measured distance of 10 mm caudal to the tibial tuberosity. (B) Constructs in the transpatellar group were augmented with a tension band wire (TBW) after drilling a transverse bone tunnel in a mediolateral direction through the middle (50% width and 50% height) of the patella using a 2.0 drill bit. Orthopedic wire was passed manually through both drill holes in the patella and proximal tibia to encircle the PT using the standard AO technique for placement of orthopedic wire. (C) Constructs in the suprapatellar group used a TBW that was placed through the proximal patellar tendon immediately adjacent to the dorsal aspect of the patella using the hub of an 18 gauge needle to facilitate uniform passage in a mediolateral direction. Distally, the wire was placed through the cranioproximal tibia as described for the transpatellar group.
(D) Constructs in the combined group were repaired using both transpatellar and suprapatellar TBW techniques as described for those groups above. Tendon repairs were augmented using 18 gauge 316 L veterinary orthopedic wire in all experimental groups where a tension band was used. In the control group (not shown), native musculotendinous constructs were tested without tenotomy, tendinous repair or TBW augmentation to verify the study methodology.

combined (transpatellar and suprapatellar) TBW technique.[1,5,7,14] Constructs in the transpatellar group (Figure 1B) were augmented with a TBW following drilling using a 2.0 mm drill bit (Securos; BITE Bit, Neuhausen, Germany) to create transverse bone tunnels in a mediolateral direction through the middle (50% width/50% height) of the patella and a mediolateral hole in the cranioproximal tibia at a measured distance of 10 mm caudal to the tibial tuberosity. Wire was passed manually through both drill holes to encircle the PT and the distal limb was then mounted in a vice. The patella was held proximally and wire tightened with wire twisters (Securos; Wire Twister TC 7″, Neuhausen, Germany) until there was removal of all slack in the wire without causing local deformation of the patella tendon.

In the suprapatellar group (Figure 1C), constructs were augmented using an adjunctive suprapatellar TBW that was placed through the PT immediately proximal to

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the dorsal aspect of the patella using the hub of an 18 gauge needle to facilitate uniform passage in a mediolateral direction to engage the medial and lateral parapatellar fibrocartilages, respectively. Distally, the wire was passed through the cranioproximal tibia as described for the transpatellar group.

In the combined group (Figure 1D), constructs were augmented using both transpatellar and suprapatellar TBW techniques as described for the designated groups above. Transosseous bone tunnels were drilled in the tibial tuberosity as described with both wires from the suprapatellar and transpatellar group traversing the single bone tunnel. In all groups (transpatellar, suprapatellar, and combined) where TBW augmentation was used, wire was twisted using wire twisters and cut to a length of three twists with wire cutters (Securos; Wire Cutters, Neuhausen Eck, Germany).

In the control group ($n = 10$), native musculotendinous constructs were tested without tenotomy, tendinous repair, or TBW augmentation, to verify the study methodology and to assess the tensile strength and stiffness of intact specimens.

2.3 | Biomechanical testing

Biomechanical testing was performed using a materials testing machine (Instron, Norwood, Massachusetts) with constructs tested at room temperature. A high-definition camera (Panasonic, Newark, New Jersey) recorded tests at 50 frames/s positioned a standardized distance of 30 cm, level with the tenotomy. The proximal tibia, tibial tuberosity, PT, and patella were all within the viewing window. Calibrated software (Matlab R2018b, Mathworks, Natcik, Massachusetts) was synchronized with video recordings using an automated triggering system to allow for simultaneous evaluation of both biomechanical data and frame data to allow for load calculation at both 1 and 3 mm gap formation.

Following placement within the custom testing apparatus (SKU-1652-1; Sawbones, Vashon Island, Washington), constructs were mounted on a 1000 N load cell. A 5 mm bone tunnel was drilled transversely through the diaphysis of the tibia and a 4 mm stainless-steel bolt passed through the clamp and pre-drilled hole to prevent rotational changes. Proximally, the remaining distal musculature of the quadriceps femoris muscle was secured proximal to the patella sesamoid using a servo-hydraulic compressive pneumatic clamp (2kN, Instron, Norwood, Massachusetts) and the PT was vertically aligned. The long axis of the tibia was then positioned at an angle of 135° to the PT using a medical goniometer.[27] The pneumatic clamp was positioned 10 mm proximal to the patella to prevent any possible interaction between the holding clamp and TBW during testing. Following positioning, specimens were preloaded to 2 N and the system recalibrated to zero. Wires for each group were then further twisted to a load of 10 N and wires cut to a length of four twists and the machine recalibrated to achieve a consistent resting baseline among specimens. Constructs were distracted at 20 mm/s until the point of failure. Load and displacement data was collected at a frequency of 100 Hz with assessment of time (seconds), displacement (millimeters), and load (newtons).

Load displacement (LD) curves were created using the tensile-testing system and subsequently identified the biomechanical variables of interest including yield, peak, and failure loads. Yield load was defined as the load at the point where the first deflection in linearity of the LD curve occurred indicating a visual change from elastic to plastic deformation of the construct. Peak load was defined as the highest measured load during each test. Failure load was defined as the load applied at the time construct failure measured by an acute load drop of >50%. Construct stiffness (N/mm) was defined as the extent to which repaired constructs resisted deformation to an applied load that was calculated at 60%–80% of yield load measured over the elastic region of the LD curve. Stiffness was calculated using a coded program (Matlab version R2018b; Mathworks). Mode of failure was recorded during testing and following review of high-speed video footage. From video footage and synchronized load data, gap formation was calculated by measuring 1 and 3 mm gaps at the shortest distance between tendon ends. Measurements were performed following calibration of digital calipers to a ruler of known length placed parallel and adjacent to the repaired construct (Image J, NIH, Bethesda, Maryland). The times (s) at which 1 and 3 mm gap formation occurred was cross-referenced with the recorded load data to calculate loads at which gap formation occurred between tendon ends. Data were recorded as "no gapping" if failure of the construct occurred prior to identification of an identifiable gap between tendon ends.

2.4 | Statistical analysis

Pilot testing was performed using $n = 9$ hindlimbs to refine the study design and perform a power analysis. Pilot data was not included within the final statistical analysis. An *a priori* power analysis was performed using pilot data and determined that ≤15 specimens/group would provide an 80% power to detect a mean difference

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of 50 ± 20 N between groups with 90% confidence. A Shapiro–Wilk test assessed the data for normality. Continuous variables were normally distributed and described using means ± SDs. A mixed linear model assessed differences in biomechanical loads and stiffness data, with experimental group considered a fixed effect and cadaver a random effect. A Fisher's exact test compared failure modes and proportional distribution of gap formation between tendon ends. All analyses were performed using a statistical software program (v.9.4, SAS, Cary, North Carolina) and *p* values less than .05 were considered statistically significant.

3 | RESULTS

No specimens were rejected at the time of specimen harvest and dissection. All construct repairs and biomechanical testing were performed without observed procedural error. Left and right hindlimbs were distributed equally among groups ($p = .44$). Mean ± SD CSA of tendons in the transpatellar, suprapatellar and combined group was 0.26 ± 0.05, 0.26 ± 0.05, 0.23 ± 0.04 with no difference ($p = .30$) between groups.

Combined transpatellar and suprapatellar TBW augmentation was superior to either transpatellar or suprapatellar groups alone (Table 1). The combined group differed regarding yield ($p = .0008$), peak ($p = .004$), and failure loads ($p = .005$). In the combined group, yield loads were 71% greater than the transpatellar ($p = .0068$) and 60% greater than the suprapatellar groups ($p = .02$) respectively. Peak loads in the combined group were 23% greater than the transpatellar group ($p = .04$), and 30% greater than the suprapatellar group ($p = .009$). Similarly, the combined group failed at greater loads compared to both transpatellar (23%, $p = .048$) and suprapatellar groups (30%, $p = .01$). Construct stiffness was greater in the combined group ($p = .04$). Mean construct stiffness of suprapatellar constructs was lower compared to other groups ($p < .002$) (Table 1).

There was no difference regarding the occurrence of 1 or 3 mm gap formation between groups (1 mm, $p = .05$; 3 mm, $p = .06$). However, the loads required to produce a 3 mm gap were greater for the combined group ($p = .036$). There was no difference in loads required to produce a 1 mm gap among groups ($p = .056$); however, a 1 mm gap was observed in 61% (11/18) of transpatellar constructs, 39% (7/18) of suprapatellar constructs, and 22% (4/18) of combined constructs (Table 2). Following a similar trend, 3 mm gaps were observed in 39% (7/18) of transpatellar, 22% (4/18) of suprapatellar, and 6% (1/18) of combined wire constructs respectively (Table 2).

Three different failure modes were observed: tissue failure, tenorrhaphy suture failure, or wire breakage. In some constructs, two modes of failure were seen concurrently. Tissue failure occurred due to patellar fracture, tibial tuberosity avulsion through the transosseous tunnel, or proximal muscle tearing at the musculotendinous junction of the quadriceps femoris muscle. For transpatellar constructs, failure occurred by core suture pull

TABLE 1 Mean ± SD yield, peak, and failure loads (newtons, N) for simulated rupture of the patellar tendon (RPT) that underwent transverse patellar tendon (PT) tenotomy and repaired using a core LL suture and SCES and augmented with either a transpatellar ($n = 18$), suprapatellar ($n = 18$), or combined technique using both a transpatellar and circumpatellar ($n = 18$) wire (18 gauge stainless steel orthopedic wire) alongside unaltered control tendons ($n = 10$).

Group	Yield load (*N*)	Peak load (*N*)	Failure load (*N*)	Stiffness (*N*/mm)
Transpatellar	277.9 ± 84.4	519.5 ± 78.1	517.5 ± 80.8	46.8 ± 11.6
Suprapatellar	298.2 ± 116.3	491.2 ± 94.8	489.1 ± 95.7	28.5 ± 56
Combined	475.7 ± 237.1	636.8 ± 154.2	634.3 ± 156.1	61.2 ± 22.5
Controls	496.0 ± 189.7	583.5 ± 120.1	582.9 ± 120.0	58.8 ± 17.0

TABLE 2 Proportions of the constructs (%) and mean ± SD loads (newtons, N) in which 1 and 3 mm gaps occurred between tendon ends during biochemical testing.

	1 mm gap formation		3 mm gap formation	
Group	Proportion (%)	Force (N)	Proportion (%)	Force (N)
Transpatellar	11/18 (61)	541.1 ± 88.1	7/18 (39)	553.6 ± 82.9
Suprapatellar	7/18 (39)	380.4 ± 138.3	4/18 (22)	414.8 ± 150.0
Combined	4/18 (22)	429.5 ± 255.3	1/18 (6)[a]	228.0 ± 0.0

[a] The reader should note the load to cause 3 mm gap formation in a single construct in the combined group likely represents a single outlier within the data set.

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through in 67% (12/18), repairs with failure due to wire unraveling in 50% (9/18), and avulsion of the tibial tuberosity in 22% of repairs (4/18). In 3/12 constructs in the transpatellar group, core suture failure occurred due to wire elongation caused by the wire first cutting through the bone prior to complete avulsion of the tibial tuberosity. In the suprapatellar group, 67% (12/18) of constructs failed by wire unraveling, 44% (8/18) by suture pull through, and 17% (3/18) by avulsion of the tibial tuberosity. Among experimental groups, fracture of the patella was only observed in the combined wire group (2/18, 11%). In the combined group, the predominant failure mode was by wire unraveling (39%, 7/18), with suture pull through (17%, 3/18). Mode of failure differed between RPT repair techniques ($p < .001$). However, mixed model analysis revealed no difference regarding the failure mode of the TBW ($p = .29$). Lastly, the predominant mode of failure in the control group was muscle tearing and avulsion from the proximal pole of the patella at the myotendinous junction (90%, 9/10).

4 | DISCUSSION

In support of our hypothesis, the use of combined transpatellar and suprapatellar orthopedic TBW augmentation in addition to a primary core and epitendinous tenorrhaphy was biomechanically superior to either transpatellar and suprapatellar wiring techniques alone. These findings are likely explained by the synergistic relationship between multiple forms of augmentation that allow load sharing between components of the repair, which is also supported by greater stiffness using the combined wiring technique. A recent study by Soula et al. compared the biomechanical properties of primary tenorrhaphies in a canine RPT model using a modified three-loop pulley technique and a three-level self-locking technique.[11] Although differences in study methodology make direct comparisons challenging, in our study, failure loads (mean ± SD) were greater (517.5 ± 80.8 N for transpatellar constructs, 489.1 ± 95.7 N for suprapatellar constructs, 634.3 ± 156.1 N for combined constructs) compared to those reported for both the three-level self-locking technique (266 ± 85.6 N) and modified three-loop pulley technique (135 ± 70 N) reported in the Soula et al. study.[11] Although direct extrapolation between studies depends on a number of interrelated factors, the superiority of ancillary methods of stabilization using TBW augmentation is apparent. These findings are likely due to reduction in load placed on the primary tendinous anastomosis and load sharing between the primary tenorrhaphy and TBW, which subsequently increases the loads to cause construct failure.

In humans, many surgical techniques for RPT repair augmentation have been reported to mitigate the direct forces placed upon the repair site during quadriceps contraction and weight bearing. Methods described include the use of either a transpatellar cable-wire cerclage or polydioxanone sutures, autograft, or tendinous allografts (Semitendinosus, Achilles tendon), or use of suture anchors.[28–34] Given the lack of available veterinary literature, the results of the present study can be compared with similar biomechanical studies cited in the human literature. A biomechanical study by Rothfeld et al. compared primary RPT repair with augmentation using a locking Krackow suture pattern with an 18-gauge TBW or use of a multifilament internal brace with FiberTape (Arthrex, Inc., Naples, Florida).[30] In this study, augmented repairs using orthopedic wire or ultra-high strength 2 mm FiberTape composed of long-chain polyethylene were superior to core RPT repairs alone with no difference reported between different augmentation methods (wire vs. FiberTape).[30] A human study by Ettinger et al. demonstrated that failure loads were greater using suture anchors compared to transpatellar augmentation using No. 2 Ultrabraid sutures (Smith & Nephew, Hamburg, Germany).[32] In humans, the biomechanical superiority of internal splint augmentation has multiple clinical benefits such as the ability for earlier weight bearing and mobilization, controlled rehabilitation, and load application to the repair site, allowing for collagenous remodeling.[30,32] In patients undergoing RPT repair, augmentation techniques have been associated with decreased postoperative complications such as decreased range of stifle motion and cartilage excoriation due to chondromalacia.[1,5,29,35]

In the present study, construct failure was decreased using combined TBW augmentation in comparison with either transpatellar or suprapatellar TBW use alone, with the predominant mode of failure seen to be due to wire unraveling at the twist. Although wire breakage is a well-documented complication in veterinary literature following TBW implementation,[3,4,7] failure of orthopedic wire due to unraveling of the knot occurs when a single increasing load is applied. Wire breakage occurs due to cyclical loading, especially in instances where bending forces are applied.[3,4,7] To date, there is a paucity of information reporting the true mechanism and location of wire failure in veterinary patients. Modifications such as the use of orthopedic wire with a greater area moment of inertia, increased number of twists, or the location of the completed twists may all play a role in construct biomechanics, and subsequently represent an area for investigation. All primary tenorrhaphies were repaired using a core LL and SCES, due to evidence supporting the biomechanical superiority of these techniques for anastomosis

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of flat tendons.[24,25,36] Although weaker than the 3LP technique, the LL pattern leads to superior apposition of the tendon ends with less bunching at the anastomosis site.[24,25,36] Failure caused by core suture pull through can likely be attributed to differing load application to the repair site rather than load application being primarily resisted by the orthopedic wire. In several constructs, there were two concurrent modes of failure seen during testing, most notably caused by the wire first unraveling causing subsequent suture pull through due to overloading of the primary tendinous repair. The incidence of suture pull through differed between transpatellar and suprapatellar wire techniques being 22% greater in transpatellar group. These findings are likely explained due to the increased construct stiffness in the transpatellar group due to the bone-to-bone interface of the wire causing load application to the repair when the wire is loaded beyond its elastic limit rather than relying on the inherent strength of native tissues. Lastly, fracture of the patella was only noted in the combined group. Patella fractures occurring either alone or in combination with patellar ligament rupture are often treated with a TBW to decrease forces generated during quadriceps contraction.[1] In a human cadaveric study by Bonazza et al., biomechanically evaluating medial patellofemoral ligament reconstruction, transosseous tunnels were associated with increased risk of patellar fracture if the anterior cortex of the patella was compromised during bone tunnel drilling.[37] This may be a possible explanation for the patellar fracture in this study and warrants further study as transosseous tunnel creation was performed in a subjective freehand manner to replicate what is performed clinically in our tertiary referral hospital.

Resistance to gap formation is a crucial component of the tenorrhaphy during the postoperative period, as gap formation is associated with adhesion formation, impaired healing and collagenous remodeling, ultimately resulting in patella alta, decreased limb function, and decreased joint range of motion.[38] Gap formation of less than 3 mm has been shown to lead to greater ultimate force and rigidity postoperatively.[38] In our study, the occurrence of gap formation was lower in the combined wire augmentation group, further supporting the biomechanical superiority of this combined technique as reported in the human literature.[39,40] In a human cadaveric study by Ravalin et al., augmented repairs following PT avulsion (No. 5 Ethibond suture or 2–0 cable) resisted gap formation to a greater degree than primary tenorrhaphies alone.[39] Similarly, a study by Gould et al. found that simulated RPT repairs using a Krakow pattern augmented with suture tape were superior compared to primary tenorrhaphy.[40] Although there were no differences in the occurrence of gap formation among study groups, this may have been due to a small sample size resulting in Type II statistical error. In several instances, gapping between tendon ends was not recorded due to construct failure prior to identification of a gap forming. Although this makes data regarding the incidence of gap formation more difficult to interpret, calculated loads at which gap formation occurred between tendon ends remain unaffected.

The limitations of this study include the use of a cadaveric model for biomechanical testing, which does not account for the effects of biological tissue healing or inflammatory mediators on collagenous remodeling. Similarly, use of linear distraction to failure testing without evaluation of cyclical loading likely underrepresents the complex and differential forces placed on the repair during different phases of the canine gait cycle. Tendon repairs will often fail within their reported range of tolerance when experiencing cyclical loading rather than peak load application or load to failure.[41] In our study, PT were sharply transected in the mid-substance region of the PT, in contrast with tendinous fraying and fibril degeneration often seen in clinical cases. We used a single transosseous tunnel, through which both wires were placed in the combined group; the effect of drilling separate tunnels and its effect on construct biomechanics is unknown. Lastly, a reported concern regarding the use of orthopedic wire for adjunctive RPT repair stabilization is wire fatigue and breakage, resulting in lameness or soft-tissue irritation ultimately necessitating removal postoperatively.[3,4,7,15] A study by Das et al. reported a greater number of patients requiring surgical reintervention to remove orthopedic wire versus use of monofilament nylon.[4] Despite these known complications, wire continues to be cited widely throughout the literature as a form of definitive fixation.[1,3] Future studies investigating the use of materials for RPT augmentation, including fiber wire and monofilament nylon, are warranted to compare the biomechanical effects of each technique and ultimately improve clinical outcomes.

In conclusion, use of a combined transpatellar and suprapatellar TBW technique using orthopedic wire as an adjunctive method of stabilization following primary canine RPT repair was biomechanically superior to either transpatellar and suprapatellar wiring techniques alone and was associated with a decreased incidence of failure. This combined adjunctive wiring technique, in addition to primary RPT repair, may offer a viable surgical option for increased repair-site strength. Further studies investigating alternative methods and materials for RPT repair augmentation are warranted.

AUTHOR CONTRIBUTIONS

McKay RM, DVM: Interpretation of the data, writing and revising the manuscript, and approval of the final version to be published. Duffy DJ, BVM&S(Hons.), MS, FHEA,

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MRCVS, DACVS (Small Animal), DECVS: Design of work performed and study methodology, construct suturing and wire augmentation, acquisition of data, interpretation of the data, writing and revising the manuscript, and approval of the final version to be published. Chang Y-J, BVetMed, MS: Acquisition of data, interpretation of the data, revising the manuscript, and approval of the final version to be published. Beamon W, DVM: Acquisition of data, interpretation of the data, revising the manuscript, and approval of the final version to be published. Moore GE, DVM, PhD, ACVIM (SAIM): Statistical analysis, interpretation of data, review of the manuscript and approval of the final version to be published.

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CONFLICT OF INTEREST STATEMENT

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