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An ex vivo biomechanical comparison of two suture materials and two pattern combinations for equine superficial digital flexor tendon tenorrhaphy

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Abstract

Objective: To compare biomechanical characteristics of three-loop pulley (3LP) pattern versus Bunnell technique (BT) using polydioxanone (PDS) suture; to determine the influence of polyester tape (PT) versus PDS on the BT for equine superficial digital flexor tendon (SDFT) tenorrhaphy; to compare BT with PT versus 3LP with PDS.

Study Design: Ex vivo biomechanical study.

Sample Population: Forty equine forelimb SDFT.

Methods: Two experiments were performed: (1) 10 SDFT pairs were repaired with 3LP or BT using PDS; (2) 10 SDFT pairs were repaired with PDS or PT using BT. Load at failure, mode of failure, load at 2 mm gap, and gap at failure were obtained using a material testing machine.

Results: In experiment 1, 3LP + PDS_1 had higher loads at failure ($p < .001$) and at 2 mm gap ($p < .001$), and smaller gap at failure than BT + PDS_1 ($p = .024$). In experiment 2, BT + PT_2 had higher loads at failure ($p < .001$) and at 2 mm gap ($p = .001$), and larger gap at failure ($p = .004$) than the BT + PDS_2. 3LP + PDS_1 and BT + PT_2 mostly failed by suture/implant pull-through while BT + PDS failed by suture breakage. BT + PT_2 had greater load ($p = .035$) and gap at failure ($p < .001$) than 3LP + PDS_1, with no difference in load at 2 mm gap ($p = .14$).

Conclusion: The use of BT may be justified over 3LP if combined with PT. However, the larger size of the PT required stab incisions in the tendon for placement and was subjectively more difficult to place than PDS.

Clinical Significance: The BT + PT, although the strongest among the tested repairs, would only be able to withstand 12%–24% of the load encountered by the SDFT at walk.

Preliminary results were presented at the ECVS Virtual Resident forum, July 2, 2020, replacing the Resident Forum which was to take place at the 29th ECVS Annual Scientific Meeting 2020 in Valencia.

1 | INTRODUCTION

Superficial digital flexor tendon (SDFT) lacerations are serious injuries that may lead to irreversible consequences including career interruption and euthanasia.[1-4] Prognosis following lacerations of the digital flexor tendons and ligaments of the palmar/plantar aspect of the distal limb is guarded, with 54%–55% of horses returning to previous athletic function and 24%–27% returning to a reduced level of performance.[2,3] Currently, primary repair of flexor tendon lacerations is recommended based on multiple studies in which it was found that transected equine SDFTs treated with tenorrhaphy were mechanically stronger and histologically superior in the scar that formed when compared to transected tendons left to heal by second intention.[2-7]

As reported by Strickland, six requirements need to be satisfied for an optimal flexor tendon repair in the human hand.[8] These principles can also be applied to equine tenorrhaphy and include: (1) the execution of the suture pattern must be easily achieved; (2) the knot, considered the weakest part of a repair,[9-11] must have great holding capacity; (3) no bulk or distortion of the repair site must be present, which would otherwise increase gliding resistance; (4) complete apposition between the transected tendon edges must be achieved; (5) intra- and extra-tendinous vascularization must be preserved and (6) the tenorrhaphy must have adequate tensile strength to support the load required during rehabilitation in order to obviate tendon repair failure.[8] In current equine literature, many tenorrhaphy techniques using a variety of different suture material and pattern combinations have been proposed, none of which achieved the required strength for immediate weight-bearing postoperatively.[2-4,6,7,12-17]

Among the numerous repair techniques proposed, the most commonly used, when there is adequate apposition of transected tendon edges, are the three-loop pulley (3LP) and the locking loop using monofilament absorbable suture material.[7,17,18] However, these repair methods are only able to withstand up to 1/3 of the maximal load encountered by the equine SDFT during weight-bearing.[13,16,19-21] This increases the risk of gap formation and suture failure at the level of the repair.[17,18] External coaptation in horses is used to reduce these complications; however, it has been recently reported that prolonged immobilization of the equine distal limb can result in permanent and irreversible changes within the metacarpophalangeal joint.[22] Furthermore, the 3LP repair leads to abundant suture material exposed on the exterior of the tendon which increases gliding resistance, serves as a nidus for infection, and facilitates the formation of peritendinous adhesions.[13,16,19-21]

The majority of repair techniques used in equine flexor tendon tenorrhaphy have been adopted from repair of flexor tendon lacerations of the human hand.[4,13,16,18,20] However, recent studies comparing load characteristics of the human Achilles tendon (AT) to equine SDFTs have found that both are functionally and clinically equivalent structures.[23,24] Therefore, AT surgery may provide a better clinical comparison for equine SDFT repair.[25] In humans, AT rupture is common and can have a significant impact on athletes.[23,26] As such, optimal repair of AT ruptures in humans continues to be an active field of research.[25] A recent technique using a polyester tape (PT) implant in a Bunnell-type suture pattern has been used successfully to treat acute AT ruptures in humans.[27,28] The PT device is manufactured from polyethylene terephthalate and is based on a human implant system called AchilloCordPlus (Neoligament, Leeds, UK).[29]

The Bunnell technique (BT) is an interlacing suture and is one of the most commonly used techniques for open AT repair in humans.[25,28,30] It is an intratendinous suture pattern, where a minimal amount of exposed suture material is located along the abaxial surfaces of the tendon. This would potentially have a reduced impact on gliding function compared to the 3LP pattern.[20] To the authors' knowledge, the use of the BT and the PT for repair of SDFT lacerations in horses has not been described.

The objectives of this ex vivo biomechanical study were: to compare strength and failure characteristics of a 3LP pattern against a BT using the polydioxanone (PDS) suture; to determine the influence of a PT implant versus PDS suture on the biomechanical properties of the BT for equine SDFT tenorrhaphy. In addition, the tensile strength characteristics at failure of BT with PT versus 3LP with PDS were also compared.

We hypothesized that a higher tensile load to failure and gap formation would be present in the BT compared to the 3LP using PDS, due to the interlacing nature of the BT suture pattern, resulting in greater interaction with the tendon matrix.[25] Moreover, we hypothesized that a higher tensile load to failure and gap formation would be present in the BT performed using the PT implant compared to the PDS due to the inherent greater strength of the PT implant compared to the PDS.[29,31] Consequently, a higher overall biomechanical strength was hypothesized for the combination of BT and PT when compared to 3LP and PDS.

2 | MATERIALS AND METHODS

2.1 | Specimen preparation

Forty forelimbs were collected from 20 adult horses, ranging in age from 5 to 21 years and weighing from

469 to 682 kg, donated by a local abattoir. Post-mortem use of animal tissues was approved by the Ethics and Welfare Committee of Glasgow, University Veterinary School (protocol No. 33a/18). Limbs were excluded if gross abnormalities involving the tendon and/or osseous-musculotendinous tissue were present on visual inspection. There were 14 geldings and 6 mares including 8 Thoroughbreds, 6 Irish Sport horses, 2 Welsh Cobs, 1 Irish Draught, and 3 crossbreed horses.

The limbs, transected distal to the antebrachiocarpal joint, were collected within 2 h of euthanasia and clipped to facilitate dissection. SDFTs were carefully isolated by transecting tendons proximally at the level of the carpometacarpal joint and distally at the level of the proximal sesamoid bones. Immediately after isolation, tendons were cleaned and dressed in gauze swabs soaked with isotonic solution (Sodium Chloride 0.9%). Tendon specimens were placed in labeled transparent bags, inside a plastic rigid container, and frozen at -70°C until testing.

On the day of testing, tendons were thawed to room temperature (20–22°C), positioned over a rigid board, and sharply transected, perpendicular to the longitudinal axis of the tendon, at midpoint using a size 22 scalpel blade. After transection, tendon edges were placed close to a millimeter-measuring tape and photographed with a camera (Casio®, Exilim, EX-ZR100) placed at a distance of 12 cm, perpendicular with the cut surface of the tendon. The mean of cross-sectional areas (CSA) for each tendon was calculated by four evaluations using ImageJ (National Institutes of Health, Bethesda, Maryland).

2.2 | Surgical treatment groups

SDFT pairs, left and right from the same horse, were randomly allocated (10 matched pairs per group) to one of two experimental groups (experiment one or experiment two) by using a random number generator (www.randomizer.org). All tenorrhaphies were executed by a single investigator (AG) to maintain consistency between repairs.

Tenorrhaphies were performed on a rigid board that had a bolted stainless-steel ruler, marked in millimeters, on its surface. Tendons were placed adjacent to the ruler and held in place using handed bar clamps (Mini one-handed bar clamp, Quick-Grip®, Irwin®) in order to accurately and uniformly perform the tenorrhaphies.

In experiment one, left and right SDFTs of each pair were randomized to be repaired with either a 3LP or BT using size 2 PDS swaged onto a CP 1/2 X 40 mm reverse cutting needle (PDS; Ethicon, Inc, New Jersey) (3LP + PDS_1 and BT + PDS_1 groups). In experiment two, left and right SDFTs of each pair were randomized to be repaired with either size 2 PDS or PT implant using the BT (BT + PDS_2 and BT + PT_2 groups).

The PT implant is a densely woven flexible tubular structure of 5 mm diameter and 800 mm length. One of the two flat ends, measuring 100 mm, is passed through the eye of a specifically designed nickel silver probe to ensure secure threading. The probe, which has a round tip and is 200 mm long with a diameter of 1.5 mm, is supplied together with the PT implant by the same manufacturer (Neoligament, Leeds, UK) (Figure 1).[29]

The 3LP and BT were performed as previously described.[13,32] Briefly, the 3LP repair consisted of three suture loops passing through the body of the tendon on both sides of the repair.[21] Core purchase length for suture bites for the 3LP was 2, 3, and 4 cm from the transected ends of tendon (Figure 2A). The BT involved placing the needle/probe in the mid-substance of the tendon. The first passage was obliquely orientated through the tenotomy site to the outer border of the tendon 2 cm from the transected end. Thereafter, the needle/probe was passed back into the tendon at a 45° angle in relation to the longitudinal axis of the tendon to the opposite side, 4 cm from the transected end. Then, the needle/probe was passed transversally through the tendon and subsequently the pattern was reversed on the opposite side and continued in the same way on the other transected end of tendon (Figure 2B). For the BT + PT_2 group, it was necessary to create a small stab incision (approximately 2 mm) using a size 15 scalpel blade at the insertion points of the implant to facilitate passage of the probe as

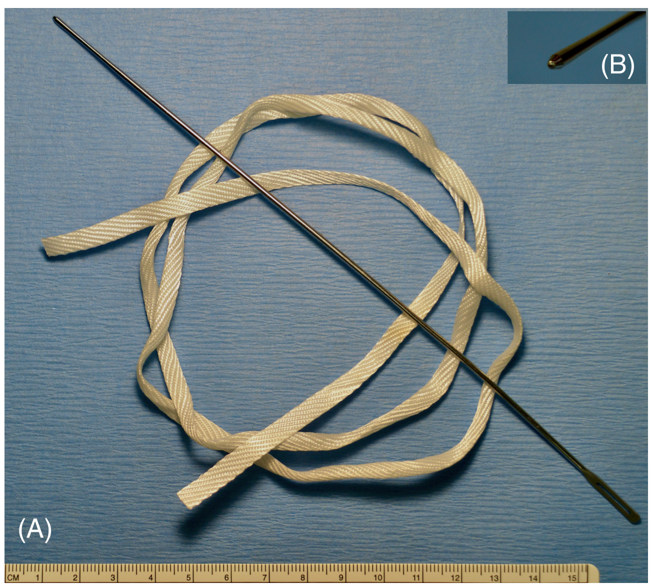

FIGURE 1 Polyester tape implant (AchilloCordPlus; Neoligament, Leeds, UK) and metallic probe (A) with a close-up image of its round tip (B)

suggested by the manufacturer.[29] Enough tension was applied to both repairs to bring the tendon ends into apposition. Suture/implants were tied with a surgeon's knot, followed by three square knots and suture/implant was cut 3 mm away from the knot.

Immediately after repair, all tendons were placed in gauze soaked in phosphate-buffered saline (PBS, Baxter Healthcare Corp, Deerfield, Illinois).

2.3 | Mechanical testing

A material testing machine (Instron 5969, Universal Testing Machine, Instron, Norwood, Massachusetts) was used to perform mechanical testing. Screw side-action grips with a distance between the clamps set at 150 mm were used to hold the repair specimens. A stainless-steel metric ruler was placed parallel and adjacent to each construct in the same plane as the tendon to allow the acquisition of measurements for videos recorded with the high-speed camera (Casio® Exilinm, Casio America Inc, Dover, New Jersey). The load (N) at failure, the load (N) at a 2-mm gap, the modality of failure, and the gap at the point of failure were measured for all the constructs. An instantaneous drop in tension, as recorded by the mechanical testing machine, was indicative of failure of the construct and was associated with suture/implant breakage or when suture/implant pulled through the tendon. As for previous studies, pull-through failure was defined as the point at which the first loop of the repair or the entire implant pulled through the tendon, for the 3LP and the BT respectively.[16,18,25,33] The load at failure was defined as the peak force recorded prior to construct failure.

Prior to testing, tendons were placed under a preload of 1 N. The displacement rate during the test was set at 8.5 mm/s until failure, as previously used in other studies.[16,18] Load (N) and displacement (mm) data, graphically represented by a non-linear load-elongation curve (Figures 3 and 4), were recorded every 10 ms using load cell software (BlueHill 2 Software, Instron Inc, Norwood, Massachusetts). A high-speed camera was used to record each test at 240 frames per second. Gap formation and load at 2 mm gap for each construct were analyzed using videographic analysis software (Kinovea, 0.9.1), which also documented mode of failure and gap at failure.

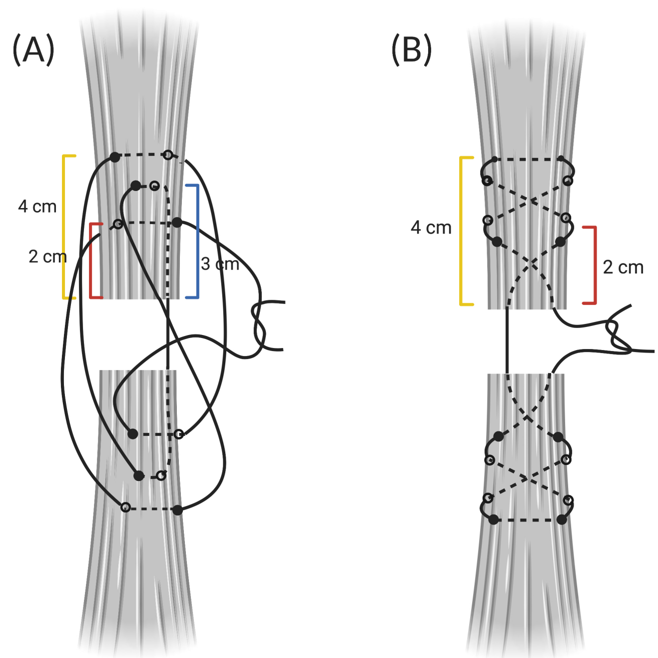

FIGURE 2 Schematic representation of the two suture techniques used. (A) Three-loop pulley (3LP) suture pattern; (B) Bunnell technique (BT)

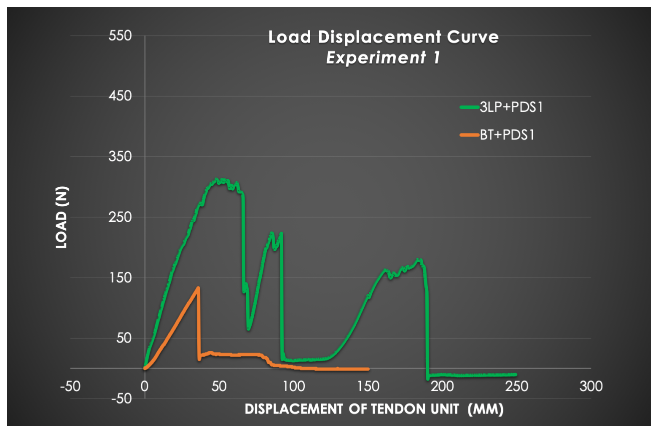

FIGURE 3 Representative sample of load–displacement curve for a matched pair of tenorrhaphies in experiment one. The x-axis is the displacement of the repairs, measured in millimeters (mm). The y-axis is the load applied to the repairs in Newtons (N). Three peaks followed by an abrupt drop in tension are observed for the 3LP + PDS1 corresponding to the pull-through failure of each loop. The first peak has been considered as the load at failure of the construct. One peak followed by an abrupt drop in tension is observed for the BT + PDS1, corresponding to the load at failure by suture breakage. 3LP, three-loop pulley; BT, Bunnell technique; PDS, polydioxanone; PT, polyester tape

2.4 | Statistical analysis

Data were arranged in Microsoft Excel (Microsoft Corporation, Redmond, Washington) and analyzed using R version 3.6.1 (R Foundation for Statistical Computing; Vienna, Austria). Normality of the data was assessed using the Shapiro-Wilk test. Each outcome was described as mean ± SD. Comparison of CSA, load to failure, load to a 2-mm gap, and gap at failure was performed using paired *t*-tests within the two experimental group (3LP + PDS_1 vs. BT + PDS_1 in experiment one, BT + PDS_2 vs. BT + PT_2 in experiment two). Unpaired *t*-tests were performed to compare the CSA, load to failure, load to a 2-mm gap, and gap at failure between the 3LP + PDS_1 group of experiment one and the BT + PT_2 group of experiment two. The frequency of mode of failure was described. A multivariate linear mixed model was used to test whether age, CSA, pattern, and suture material were significant predictors of the strength variables (load at failure, load to create a 2-mm gap, and gap at failure). The model was run using the R package "lme4" and the drop1 function was used to test a null model that included all of the listed variables to an alternative model that excluded one variable. The horse ID was added as a random effect to control for the effects of within-subject correlations. Significance for all analyses was set at $p \leq .05$.

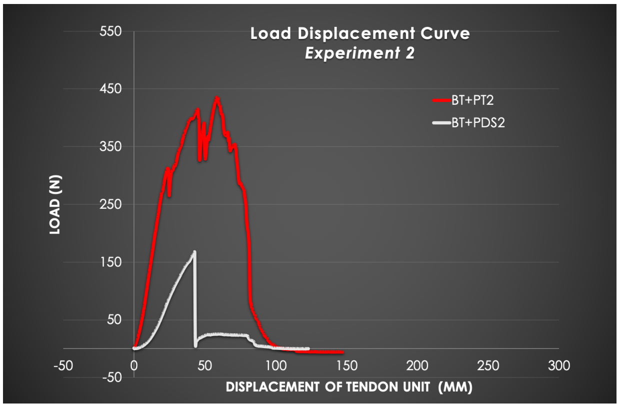

FIGURE 4 Representative sample of load–displacement curve for a matched pair of tenorrhaphies in experiment two. The x-axis is the displacement of the repairs, measured in millimeters (mm). The y-axis is the load applied to the repairs in Newtons (N). In the BT + PT2 curve, small drops in tension are observed which correspond to the gradual pull-through of the implant. These precede the highest peak, followed by an abrupt drop in tension, which corresponds to the load at failure. One peak followed by an abrupt drop in tension is observed for the BT + PDS2, corresponding to the load at failure by suture breakage. 3LP, three-loop pulley; BT, Bunnell technique; PDS, polydioxanone; PT, polyester tape

3 | RESULTS

All 40 repaired tendons were tested successfully. The Shapiro-Wilk test suggested the assumption of normality was reasonable for all these outcomes since all the *p* values were above .05 cut-off (lowest $p = .07$).

In experiment one, the mean age of horses was 11.4 ± 5.3 years. There were three mares and seven geldings. The mean CSA was $127 \pm 18.2\ mm^2$ and $129.3 \pm 16.2\ mm^2$ for the tendons in the 3LP + PDS_1 and BT + PDS_1 groups, respectively. There was no difference in mean CSA between group ($p = .226$). The 3LP + PDS_1 group failed at a mean of 319.6 ± 69.5 N, which was greater ($p < .001$) than the mean load at failure of the BT + PDS_1 group (148.5 ± 17.3 N) (Table 1). Similarly, the mean load to create a 2-mm gap for the 3LP + PDS_1 group (150.1 ± 32.3 N) was higher ($p < .001$) compared to the BT + PDS_1 group (27 ± 7.2 N) (Table 1). The mean gap at failure was larger ($p = .024$) in the BT + PDS_1 group (36.7 ± 4.9 mm) compared to the 3LP + PDS_1 group (27.4 ± 8.2 mm) (Table 1). All tendons repaired in the BT + PDS_1 group failed by suture breakage. Of the 3LP + PDS_1 repairs, eight failed by suture pull-through, and the remaining two failed by suture breakage (Table 1).

In experiment two, the mean age of horses was 10.6 ± 5.3. There were three mares and seven geldings. There was no difference ($p = .077$) in mean CSA for tendons in BT + PDS_2 ($156.1 \pm 52.6\ mm^2$) and BT + PT_2 ($141.5 \pm 37.9\ mm^2$) groups. The BT + PT_2 group failed at a mean of 437.5 ± 142.8 N, which was greater ($p < .001$) than the mean load at failure of the BT + PDS_2 group (154 ± 12.5 N) (Table 2). Similarly, the mean load to create a 2-mm gap for the BT + PT_2 group (114.8 ± 63.3 N) was higher ($p = .001$) than the BT + PDS_2 group (36.2 ± 11.6 N) (Table 2). The mean gap at failure was larger ($p = .004$) in the BT + PT_2 group (55.1 ± 12.6 mm) compared to the BT + PDS_2 group (34.7 ± 8.3 mm) (Table 2). All tendons repaired in the BT + PDS_2 group failed by suture breakage. In the BT + PT_2 group only one construct

TABLE 1 Failure of tendon repairs in experiment one: 3LP + PDS_1 versus BT + PDS_1

Repair	Material	Load at failure (N)	Load to create a 2-mm gap (N)	Gap at failure (mm)	Mode of failure
3LP	PDS	319.6 ± 69.5^a	150.1 ± 32.3^a	27.4 ± 8.2^a	Suture pull-through (8) and breakage (2)
BT	PDS	148.5 ± 17.3^b	27 ± 7.2^b	36.7 ± 4.9^b	Suture breakage (10)

Notes: Values are expressed as mean ± SD. Within each column, means with the same superscript are not significantly different ($p > .05$). Within each column, values with different superscript letters differ significantly ($p < .05$).

Abbreviations: 3LP, three-loop pulley; BT, Bunnell technique; PDS, polydioxanone.

TABLE 2 Failure of tendon repairs in experiment two: BT + PT_2 versus BT + PDS_2

Repair	Material	Load at failure (N)	Load to create a 2-mm gap (N)	Gap at failure (mm)	Mode of failure
BT	PT	437.5 ± 142.8^a	114.8 ± 63.3^a	55.1 ± 12.6^a	Implant pull-through (9) and breakage (1)
BT	PDS	154 ± 12.5^b	36.2 ± 11.6^b	34.7 ± 8.3^b	Suture breakage (10)

Notes: Values are expressed as mean ± SD. Within each column, means with the same superscript are not significantly different ($p > .05$). Within each column, values with different superscript letters differ significantly ($p < .05$).
Abbreviations: BT, Bunnell technique; PDS, polydioxanone; PT, polyester tape.

TABLE 3 Failure of tendon repairs in the comparison between 3LP + PDS_1 versus BT + PT_2

Repair	Material	Load at failure (N)	Load to create a 2-mm gap (N)	Gap at failure (mm)	Mode of failure
3LP	PDS	319.6 ± 69.5^a	150.1 ± 32.3^a	27.4 ± 8.2^a	Suture pull-through (8) and breakage (2)
BT	PT	437.5 ± 142.8^b	114.8 ± 63.3^a	55.1 ± 12.6^b	Implant pull-through (9) and breakage (1)

Notes: Values are expressed as mean ± SD. Within each column, means with the same superscript are not significantly different ($p > .05$). Within each column, values with different superscript letters differ significantly ($p < .05$).
Abbreviations: 3LP, three-loop pulley; BT, Bunnell technique; PDS, polydioxanone; PT, polyester tape.

failed by implant breakage and the rest of the constructs failed by implant pull-through (Table 2).

Comparisons between the biomechanical properties of 3LP + PDS_1 group of experiment one and BT + PT_2 group of experiment two were also performed. There was no difference in mean tendon CSA ($p = .30$) and age of horses ($p = .74$) between these two groups (mean CSA in 3LP + PDS_1 127 ± 18.2 mm^2; mean CSA in BT + PT_2 141.5 ± 37.9 mm^2). The mean load at failure was higher ($p = .035$) in the BT + PT_2 group (437.5 ± 142.8 N) compared to 3LP + PDS_1 group (319.6 ± 69.5 N) (Table 3). There was no difference ($p = .14$) in the load to create a 2-mm gap between the two groups (mean load to 2 mm gap in BT + PT_2 was 114.8 ± 63.3; mean load to a 2-mm gap in 3LP + PDS_1 was 150.1 ± 32.3) (Table 3). The gap at failure was larger ($p < .001$) in the BT + PT_2 group (55.1 ± 12.6 mm) than the 3LP + PDS_1 group (27.4 ± 8.2 mm) (Table 3). The mode of failure for both repair groups was mostly suture/implant pull-through (8/10 in the 3LP + PDS_1, 9/10 in the BT + PT_2) (Table 3).

Results from the multivariate linear mixed model analysis suggested that the horse's age and the tendon's CSA were not associated with the biomechanical variables ($p = .44$ and $p = .08$, respectively). Also, in line with the *t*-tests performed, the pattern and material were statistically significantly associated with the biomechanical variables ($p < .001$).

4 | DISCUSSION

This study compared two patterns and two suture materials in an attempt to identify a repair combination that would provide the greatest biomechanical strength for equine SDFT tenorrhaphy ex vivo.

Recent comparative studies have identified biomechanical similarities between the equine SDFT and the human AT.[23,34] Although they are not the same structure anatomically, both are energy-storing tendons and function close to failure level.[23,34] The BT is commonly used for open human AT tenorrhaphy and therefore it has been investigated as a potential suitable repair method for equine SDFT.[25,28,30]

In experiment one of this study, the 3LP pattern was compared to the BT using the same suture material (size 2 PDS). The results indicate that the 3LP + PDS_1 outperformed the BT + PDS_1, having a greater load at failure, a greater load to create a 2-mm gap, and a smaller gap at failure. This could be explained by the fact that in the 3LP pattern, six strands of suture are present across the site of tendon transection compared to the two strands in the BT.[35,36] As reported in human literature, the number of core suture strands across a repair site is positively correlated to the strength of repair—the greater the number of suture strands, the greater the strength of repair.[37,38] With only two suture strands crossing the site of tendon transection for the BT, the two strands are subjected to higher loads compared to the six suture strands of the 3LP. This could also explain the difference observed in the modality of failure for the two constructs.[39] The 3LP + PDS_1 mostly failed by suture pull-through, while the BT + PDS_1 failed by suture breakage, in agreement with previous studies.[13,17-20,36]

Another difference between the two repairs is the location of the knot—the knot is placed externally in the 3LP and internally at the site of tendon transection for the BT. The decision to place the knot between the transected ends in the BT repairs was based on the human AT tenorrhaphy technique and on potential clinical significance.[27,28] Knots placed within the rupture site limit interference with tendon gliding function and reduces the risk of peritendinous adhesion formation.[9,10] However, it is possible that the physical presence and the bulkiness of the knot in this location could facilitate gap formation, and this could explain the lower mean load to create a 2-mm gap for the BT compared to the 3LP pattern. Therefore, the results of this experiment indicate that there would be no advantage in performing the BT using PDS over the 3LP using PDS for equine SDFT tenorrhaphy in regards to strength and mechanical resistance to failure.

We hypothesized that the biomechanical properties of the BT could be improved by using a stronger material, as described in human AT repair studies.[27,39] In fact, the PT (AchilloCordPlus; Neoligament, Leeds, UK), used in this study, is reported to have a three-fold greater breaking strength than the size 2 PDS (585 ± 21 N and 193.0 ± 28.35, respectively).[29,31] In experiment two, the BT + PT_2 combination was superior in strength compared to the BT + PDS_2 although a smaller gap at failure was observed for the BT + PDS_2 compared to the BT + PT_2. This is most likely due to the substantial differences between the two materials tested. The PT implant is a dense, woven network of nondegradable synthetic polymer with a larger diameter and a greater ultimate strength than the monofilament size 2 PDS.[27,29] The larger contact area between tendon and the PT may increase the coefficient of friction between the tendon and thread surface, resulting in the PT + BT construct having a higher holding capacity.[39] The strength of the PT suture material appears to be greater than the force required to disrupt the collagen fibrils of the tendon, resulting in failure by suture pull-through.[40] This gradual disruption of the tendon fibers by the PT during the distraction phase, as observed in the video analysis, slowed down the pull-through process, resulting in a larger gap at the moment of failure. This confirms that the PT was stronger than PDS in the equine SDFTs in this study, and supports the use of PT over PDS in a BT pattern, as suggested by similar repair studies in human ATs.[27,39]

Despite the superior biomechanical strength observed for the 3LP pattern in experiment one and PT material in experiment two, it was not considered appropriate to test the 3LP in combination with PT. Considering the larger diameter and composition of the PT compared to the PDS, attempting a 3LP repair with PT would have resulted in significant extratendinous non-absorbable suture material, limiting its clinical application when combined with a 3LP for equine tenorrhaphy.

However, we were interested in determining if there were any differences in strength or characteristics of repair failure between tendons repaired with a BT + PT and a 3LP + PDS. The BT + PT_2 repair appeared to withstand higher loads compared to the 3LP + PDS_1, having a greater load at failure. However, according to this result, the BT + PT_2 repair would only be able to withstand 12%–24% of the load normally encountered by the SDFT at walk, which is reported to range from 1845 to 3559 N.[13,16,19-21,41,42] Both constructs failed mostly by suture/implant pull-through, however, the dynamics of this process appeared to be different: in the 3LP + PDS, the suture sharply cut through the tendon fibers, while in the PT + BT the higher holding capacity of the PT caused a more gradual separation of the transected tendon ends, explaining the larger gap at the moment of failure. In addition, no differences were observed in the forces required to create 2 mm gap for the BT + PT_2 compared to the 3LP + PDS_1. The load at 2 mm gap is considered a more relevant parameter in vivo, based on the potential clinical consequences, compared to the ultimate load at failure and gap at failure.[13,16-20,43] In human and canine studies, gaps larger than 1–2 mm at the site of repair resulted in impaired healing and had a negative impact on tendon function long-term.[44,45] With the presence of a gap, healing occurred by second intention, leading to increased gliding resistance, peritendinous adhesion formation, reduced repair strength, and a greater risk of repair failure in the early phases of healing.[17,18,25,35,43,46] No study has evaluated the impact of gap formation on equine tenorrhaphy, however, it can be assumed that similar complications would occur in horses with gap formation at the site of repair. A way to limit the gap formation between the tendon ends is the use of a circumferential epitenon repair, for example, the Lin-locking technique or continuous suture.[17,47] It is reported that complete circumferential sutures can increase repair strength up to 70% over core sutures alone.[17,47]

While BT repairs were stronger when using PT, there are other characteristics of the BT repair using PT that could limit its clinical application for equine tenorrhaphy. When suturing tendon specimens, we found that the BT + PT_2 was more difficult to place compared to the other patterns, mainly due to the larger diameter of the PT compared to PDS. Moreover, although BT + PT_2 perceptively led to a better anatomic apposition of tendon ends and less distortion of the construct, the passage of the metallic probe through stab incisions resulted in focal areas of tendon fiber separation, which could have weakened the construct.

The outcome of this study provides insights on the biomechanical performance of different SDFT repairs; however, it has some limitations that need to be taken into consideration. First, this is an ex vivo study and therefore does not take into consideration factors that occur physiologically during tenorrhaphy, such as adhesion formation, effect of the construct on tendon vascularization, and tissue reactivity. Secondly, the use of linear biomechanical testing does not reflect the physiologic conditions to which a tendon is subjected. Cyclic loading may be more representative of physiologic conditions encountered by repaired tendon, however, it does not allow for easy comparison between studies that aim to evaluate the strength of repair and mode of failure, as described in this study. A third limitation was the use of sharp transection of the tendons prior to repair, which would not be representative of traumatic tendon lacerations clinically. However, sharp transection was chosen to allow for a better comparison of gap formation and repair failure across all specimens.

In conclusion, based on the superior load at failure and equivalent load at 2 mm gap, the use of the BT for equine SDFT tenorrhaphy may be justified over the 3LP if combined with a strong suture material such as the PT. Although the BT + PT provides a stronger tenorrhaphy technique compared to the 3LP + PDS, the loads are still far below the forces encountered by the equine SDFT at walk. Studies are still needed to identify a repair technique that will be able to withstand load closer to those seen in vivo, and also provide adequate resistance to gap formation. Based on this investigation, the BT pattern does not appear to meet these expectations.

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AUTHOR CONTRIBUTIONS

Andrea Giacchi: Performance of tendon transection and suture repair of experimental constructs, analysis of biomechanical testing and gapping data, statistical analysis of data, interpretation of data, writing and drafting of the study, revision of the study, and final approval of the submitted article; Mattie A. McMaster: Design of study performed, oversight of suture repairs, assistance during biomechanical testing and setup, assistance in writing and drafting of the work, review of data collected, revision of the study, and final approval of the submitted article.

CONFLICT OF INTEREST

The authors declare no conflict of interest related to this report.

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