Biomechanical Testing of a Novel Suture Pattern for Repair of Equine Tendon Lacerations

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Objective: To compare *in vitro* biomechanical properties of a novel suture pattern to a current standard for primary repair of equine superficial digital flexor tendon (SDFT) laceration.
Study Design: *In vitro* randomized, paired design.
Animals: Cadaveric equine forelimb SDFT (n = 24).
Methods: The 3-loop pulley (3LP) and 6-strand Savage (SSS) suture patterns were applied to transected equine SDFT. Ultimate failure load, stiffness, mode of failure, and load required to form a 3-mm gap were obtained using a materials testing system and synchronized high-speed video analysis. Statistical comparisons were made using Student's t-test, with significance set at $P < .05$.
Results: The SSS repair failed at a higher ultimate load (421.1 N ± 47.6) than the 3LP repair (193.7 N ± 43.0; $P < .001$). There was no significant difference in stiffness ($P = .99$). Failure mode was suture breakage for all SSS repair and suture pull through for all 3LP repair. The maximum load to create a 3-mm gap in the SSS repair (102.0 N ± 22.4) was not significantly different from the 3LP repair (109.9 N ± 16.0; $P = .27$).
Conclusions: SSS tenorrhaphy has improved strength and resistance to pull through compared with 3LP for equine SDFT in a single load-to-failure test. Load required to form a 3-mm gap was not significantly different between SSS and 3LP.

Lacerations involving the digital flexor tendons (FTs) in horses can be career and life threatening,[1–4] with a guarded prognosis for return to athletic performance; 18–55% of horses returning to their previous level of performance.[1,3,5] Primary reconstruction of lacerations is recommended in horses to improve healing.[2]

The superficial digital flexor tendon (SDFT) and deep digital flexor tendon (DDFT) are part of a dynamic apparatus including the suspensory ligament that slings the metacarpo/tarsophalangeal joint in a suspended orientation above the ground. This suspensory apparatus absorbs shock and stores elastic energy during locomotion, and contributes to weight bearing in the standing horse.[6] In this role, even during minimal exertion such as walking, the SDFT experiences load as high as 3559 N (363 kg), and strain of 2–5%.[7–11] Anatomically, the SDFT is the more commonly lacerated structure because of its more superficial location (Fig 1A).

Given the biomechanical role of the SDFT, and the large strain placed upon it, surgical repair after traumatic laceration is challenging. In addition to loss of tissue from traumatic injury that makes apposition of tendon ends difficult, tenorrhaphy of the SDFT is prone to gap formation. Currently recommended tenorrhaphy techniques frequently result in gap healing with excessive scar formation and frequent construct failure despite reduction of early strain with external coaptation.[2,4] Because of these problems, development of a strong repair that minimizes gap formation is crucial to improve treatment of FT lacerations in horses.[4,12–14] Although several suture patterns have been assessed in horses, an ideal suture technique for repair of FT lacerations has not been identified.[4,15,16]

To achieve the most desirable outcome, the ideal tenorrhaphy suture pattern would provide (1) a strong repair, (2) minimal gap formation, (3) minimal adhesion formation, and (4) minimal constriction of vascular supply. Previous *in vitro* and *in vivo* studies in human cadavers and animal models have identified the properties of tenorrhaphy that contribute to these qualities. These include core purchase length,[17,18] strand number and size,[19–21] and grasping *versus* locking attributes.[22] Whereas studies of human FT reconstruction focus on a strong repair to withstand postoperative physiotherapy,[23,24] a repair with similar qualities is desired in equine surgery to endure the strains placed on the repair by immediate postoperative weight bearing.

Historically, a variety of suture patterns and techniques have been evaluated in the horse.[4,15,25] Results of these studies suggest the 3-loop pulley (3LP; Fig 1B) compares

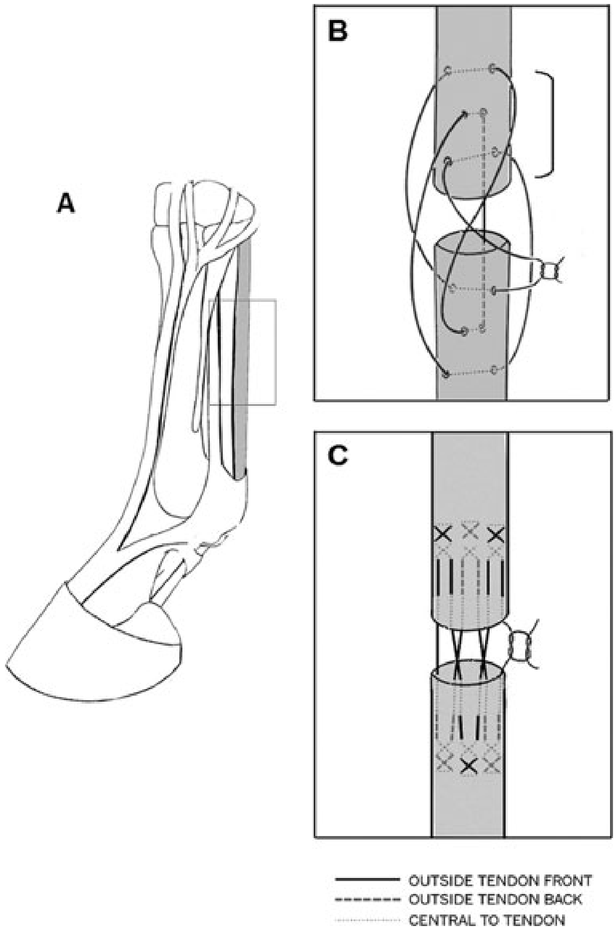

Figure 1 (A) Region of tendon specimen used in testing. (B) Graphical representation of tenorrhaphy pattern used in 3-loop pulley (3LP) repair. Bracket indicates core purchase length that was uniform at 20 mm. (C) Graphical representation of tenorrhaphy pattern used in 6-strand Savage (SSS) repair.

favorably to other patterns, such as the compound-locking loop (CLP), and has been recommended for primary tenorrhaphy in the horse.[25] In particular, the 3LP resisted gap formation better than the CLP; however, the low ultimate failure load of the 3LP pattern (31.5 ± 4.0 kg) and failure by pulling through the tendon rather than suture failure suggest that tenorrhaphy in equine FTs can be improved.

The 6-strand Savage (SSS) technique (Fig 1C) is routinely used in human hand surgery for tendon repair, and has compared well biomechanically with other suture patterns.[26–28] The SSS uses a grasping mechanism to engage tendon fibrils in the longitudinal axis for greater strength. In contrast, the 3LP pattern relies on collagen cross-linking and other interfibril connections to resist suture pull through, as it is neither a grasping nor locking pattern. Ideally, the suture patterns should be compared controlling for the variables of core purchase length, suture material size, and strand number between the 2 patterns, focusing the investigation on the intrinsic qualities of the tenorrhaphy under load.

Our purpose was to compare a novel tenorrhaphy pattern for equine tendon repair, the SSS technique, with the currently recommended pattern, the 3LP, in an *in vitro* model. We hypothesized that the SSS will provide a stronger repair that is more resistant to gap formation than the 3LP pattern in an *in vitro* model. Additionally, we hypothesized that failure mode for the SSS will occur by suture breakage, and the 3LP will fail primarily by suture pulling through the tendon tissue.

MATERIALS AND METHODS

Experimental Design

The SSS and 3LP suture techniques were applied in an *in vitro* model of tenorrhaphy and their biomechanical qualities compared in a randomized, paired design; the 3LP was performed on 1 forelimb, and the SSS on the contralateral limb. The same surgeon (EE) performed all tenotomies and tenorrhaphies to ensure consistency. The same suture (2 polydioxanone) was used, in a 6-strand continuous pattern for each, meaning that the strand crossed the tenotomy site 6 times. Identical 5-mm bites were made from transection site, and identical core purchase lengths were used (the distance from tenotomy to most distant suture placement, see Fig 1B). The ultimate failure load, stiffness, mode of failure, and the load required to create a 3-mm gap were computed by performing tensile tests.

Sample Preparation

Pairs of forelimb SDFTs were collected from 12 adult horses euthanatized for reasons other than musculoskeletal injury. The horses were 5 Thoroughbreds, 2 Warmbloods, 1 Warmblood cross, 1 Thoroughbred cross, 1 Arabian, 1 Quarter Horse cross, and 1 Draft cross. Mean age was 12 years (range, 2–25 years old) and there were 7 geldings and 5 mares.

The FT specimens were isolated in the metacarpal region from a point immediately distal to the carpal canal to the proximal aspect of the proximal sesamoid bones. The FTs were dissected free from any other soft tissue and the paratenon removed. The specimens were then wrapped in a towel moistened with saline (0.9% NaCl) solution and sealed in plastic before freezing. Tendon specimens were preserved at −70°C until they were transported frozen on dry ice to the testing laboratory.

After thawing to 30°C, each SDFT was transected transversely at the same location: 50% of the distance between the carpometacarpal joint and the proximal sesamoid bones for each paired tendon specimen, to ensure similar cross-sectional area between repair methods in each pair of tendons. Next, the 3LP or SSS was used to repair the transected tendon ends of the randomized, paired SDFT using 2 polydioxanone on a preswaged CP (cutting point) 0.5 × 40 mm reverse cutting needle (Ethicon Inc., Somerville, NJ). The tissue was kept moist by repeated application of saline solution during preparation.

A metric ruler was placed adjacent to the tendons during the tenorrhaphy to ensure that identical spacing was used for suture location in each of the specimens. This entailed starting 5 mm from the transected ends, and incorporating 20-mm core purchase length from the tenotomy for each suture pattern (Fig 1). Additionally, the tendons were marked 5 mm from the transected ends at the repair site as a tracking reference for the video capture and analysis software. The suture was knotted using a surgeon's knot followed by 5 single throws. The tenorrhaphies were secured such that the tendon ends were tightly apposed with no slack in the suture.

Biomechanical Testing

An Instron ElectroPuls 1000 Material Testing System (Instron Inc., Norwood, MA), with a load cell of static capacity of ±710 N was used to perform tensile tests on the tendons (Fig 2A). Custom-designed cryogrips were used to secure the specimens for testing and were engineered from 6061 aluminum to avoid slippage (Fig 2B). In brief, the aluminum grips were submerged in a sublimated dry ice and acetone bath for 3 minutes. Once chilled to −78.3°C, the grips were removed from the bath, the end of each tendon specimen inserted in the well with phosphate buffered saline (PBS, Baxter Healthcare Corp., Deerfield, IL). The cryogrips immediately froze to each end of the tendon specimen and the test was immediately performed. The samples were placed under preload (1 N) before commencing the test, and data were collected every 8 ms during the test. The experiments were conducted in load control at 25 mm/sec until failure occurred. Failure was defined as either suture breakage or pull through. Load at failure was recorded in Newtons (N). Failure mode was recorded manually and reviewed using high-speed videography.

Elongation and gap formation were simultaneously measured by using a high-speed digital video camera (APX-RS Photron USA, San Diego, CA) synchronized with the material testing system load cell data collection software (BlueHill 2, Instron Inc.). Specifically, markers on the surface of the specimens and the ends of the tendons were tracked using high-speed videography (125 fps). Videographic analysis software (ProAnalyst, Xcitex Inc., Cambridge, MA) was used to track the distraction of the markers and tendon ends, observe gap formation, and record the mode of construct failure. The tendons were kept moist during mechanical testing by application of saline solution at 30°C. The tensile load that induced 3-mm gap formation was determined using the ProAnalyst software. By plotting the load *versus* deformation of the specimens, a nonlinear load deformation curve was obtained for each tenorrhaphy (Figs 3A, B). Stiffness was determined by calculating the slope of the linear region before the yield point of each load deformation curve.

Data Analysis

Statistical analysis was performed using software (SAS JMP 8, SAS Institute, Cary, NC). Data from all tendons were included in descriptive statistics and statistical analyses. Data are reported as mean ± SD. Biomechanical data comparing the tenorrhaphy patterns were analyzed pairwise using Student's t-test. Significance was set at $P < .05$.

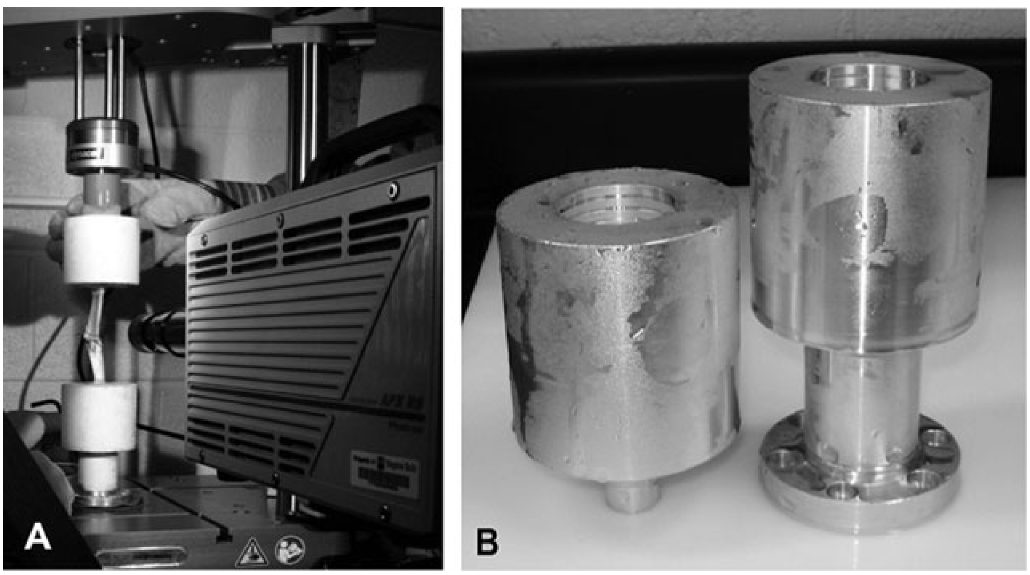

Figure 2 (A) Biomechanical testing apparatus showing cryogrips in materials testing machine with testing specimen in place. (B) Detail view of custom designed and manufactured cryogrips.

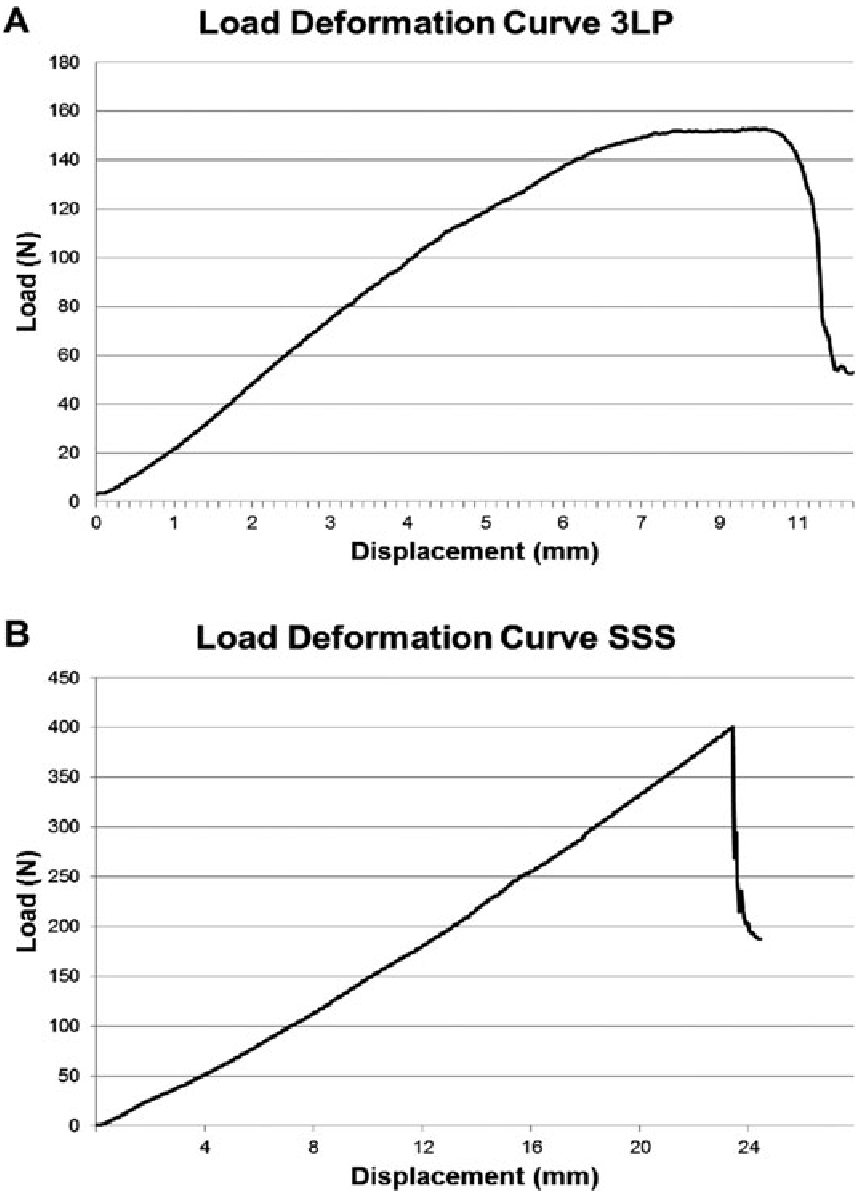

Figure 3 (A) Representative load deformation curve for 3-loop pulley (3LP) repair. (B) Representative load deformation curve for 6-strand Savage (SSS) repair.

RESULTS

No grip failure or slippage occurred during testing.

Load at Construct Failure, Failure Mode and Stiffness (Table 1)

Mean ± SD ultimate failure load for the SSS repair (421.1 N ± 47.6) was significantly higher than the 3LP repair (193.7 N ± 43.0; $P < .001$). Failure mode was suture breakage for all SSS repairs and suture pull through for all 3LP repairs. Mean stiffness of the SSS repair (19.5 ± 2.3) was not significantly different than the 3LP repair (19.4 ± 4.6; $P = .99$).

Load at 3-mm Gap Formation (Table 2)

All repairs were observed to form at least 3 mm of gap between the sutured ends before failure. Mean maximum load to create a 3-mm gap in the SSS repair (102.0 N ± 22.4) was not significantly different from the 3LP repair (109.9 N ± 16.0; $P = .27$).

Table 1 Ultimate Failure Load, Mode of Failure, and Stiffness Data.

	Failure (N)		Failure Mode		Stiffness (N•mm^{-1})	
Horse	SSS	3LP	SSS	3LP	SSS	3LP
1	455.9	144.8	Breakage	Pull through	20.0	11.0
2	356.9	155.5	Breakage	Pull through	16.3	22.5
3	399.3	186.8	Breakage	Pull through	19.7	16.6
4	383.3	151.1	Breakage	Pull through	21.5	20.6
5	473.1	189.6	Breakage	Pull through	23.2	14.4
6	405.2	275.6	Breakage	Pull through	19.5	18.6
7	368.9	205.2	Breakage	Pull through	19.2	17.3
8	400.4	182.4	Breakage	Pull through	14.5	15.4
9	422.0	271.4	Breakage	Pull through	20.7	21.2
10	402.1	168.7	Breakage	Pull through	17.8	24.1
11	513.1	218.3	Breakage	Pull through	20.7	21.3
12	473.6	174.8	Breakage	Pull through	20.5	30.5
Mean	421.1	193.7			19.5	19.4
SD	47.6	43.0			2.3	5.1

Table 2 Tensile Load that Produced 3-mm Gap.

	Load at 3-mm Gap (N)	
Horse	SSS	3LP
1	118.9	98.1
2	83.2	81.2
3	118.0	115.6
4	116.6	97.0
5	107.3	122.1
6	123.8	122.9
7	112.1	96.2
8	63.8	112.6
9	90.9	118.3
10	60.5	96.2
11	124.5	121.0
12	104.9	137.6
Mean	102.0	109.9
SD	22.4	16.0

DISCUSSION

We compared biomechanical properties of two 6-strand suture patterns using paired equine SDFT cadaver specimens. Our results support the hypothesis that the SSS suture pattern withstands significantly greater maximum load at failure than a 3LP pattern in equine SDFTs and mode of failure for the 3LP pattern was suture pull through rather than breakage, *in vitro*, consistent with previous studies.[15,25] By comparison, failure mode of the SSS was because of suture breakage in all tests.

Our results do not demonstrate a significant difference in resistance to gap formation during single load-to-failure testing between the 2 tenorrhaphy patterns. This was surprising, considering the 3LP exclusively failed by pulling through the tendon tissue. We expected the grasping SSS pattern would be more resistant to gap formation, because early gap formation may occur from suture pull through. One explanation for this result is that early gap formation (3 mm) occurred through stretching of the suture material for both suture patterns. This would explain the similar loads at which the 3-mm gap formed, because the suture and its material properties are the same in each group. In contrast with our single load to failure testing, the SSS has been shown to be more resistant to gap formation and failure after cyclic loading when compared to other patterns used in human hand surgery.[29] Further studies are necessary to determine if the SSS has benefits in reducing gap formation in a cyclic loading test in comparison to the 3LP in horses.

Because of low tensile strength of the traditional tendon repair relative to the forces placed on the tendon immediately postoperatively, casting of the limb in slight flexion has been standard practice after FT tenorrhaphy in horses. Earlier studies report *in vivo* load for equine SDFT as 362.9 kg (equivalent to 3559 N) at the walk without a cast.[7] Our data for the 3LP suggest that the repair is capable of supporting ~5% of the load placed on the SDFT before construct failure occurs. By comparison, the SSS is able to support greater than twice the load before failure (12%). Whereas external coaptation would still be necessary during the early convalescent period, the increase in tensile strength offered by the SSS is advantageous to withstand load that still occurs within a cast as the tendon ends retract, as well as for cases where debridement or tissue loss shortens the available tendon to repair.

Other forms of FT repair have been reported including plating with absorbable poly-l-lactic acid (PLA)[30] and stainless steel.[31] Plating equine DDFT with PLA demonstrated an ability of the repair to withstand 38% of load placed on the tendon at the walk (1507.08 N ± 184.34). Stainless steel plates were found to support a similar load (406.2 N ± 69.6)[31] to that we found with SSS. Although strong, plating for tendon repair places a large amount of foreign material and increased bulk at the repair site. *In vivo* compatibility and the effects of these repairs on blood supply, gliding, and adhesion formation are unknown, but PLA plating might logically have a negative effect on these variables.

Gliding function and the ability to withstand early mobilization are important to human hand tendon repair, and have been studied extensively using a variety of patterns and adhesion prevention strategies.[32–35] For horses, it has been suggested that the 3LP might inhibit gliding[15] because of the presence of excess suture material outside the tendon matrix. Additionally, excess exposed suture may also predispose the site to adhesion formation, and is not preferred for repair within the FT sheath.[36] Because of these risks, a suture pattern like the SSS, with minimal exposed suture that possesses qualities of improved strength[29] and low adhesion formation[37] is desirable.

Limitations of our study include frozen storage of tendons, the age range of the horses used (2–25 years), and use of cryogrips. Tendon biomechanics can be affected by freezing[38] and age[39] of tendon; however, the paired design of this study should mitigate these effects. Specifically, freezing has been shown to increase stiffness over time; however, ultimate failure strength was not significantly affected after 360 days of frozen storage.[38] Whereas influence of age and exercise would be expected to apply similarly to each tendon in this paired design, it is possible that they might have different effects on each different type of suture pattern. Determining the effect of age and exercise on tenorrhaphy pattern was outside the scope of this study.

Cryogenic clamps have been used in biomechanical studies of tendon to avoid slippage and to maintain an even application of tensile load throughout the tendon.[40,41] Previous studies suggest that using cryogenic clamps to secure tendon ends results in a steep temperature gradient at the fixation site and does not influence the temperature of the specimen 6 cm from the site of clamp application.[42–44] In our study, the cryogrips were >6 cm distant from tenorrhaphy. Moreover, testing was completed within 2 minutes of grip application, and outside the grip area, the tendon remained unfrozen during testing. Importantly, no slippage occurred during testing.

We did not address tendon perfusion and biomechanical properties after cyclic loading in this study, both of which are important for *in vivo* repair. Studies performed using cadaveric human and porcine tendon suggest that the biomechanical properties of the tenorrhaphy change after cyclic loading;[45–47] it will be important to study the SSS repair's resistance to cyclic fatigue.[29,45] An advantage to the 3LP is superior maintenance of tissue perfusion in an experimental model in comparison to a locking loop pattern.[48] It is unknown what effects the grasping nature of the SSS could have on perfusion of a lacerated tendon. However, the grasping bites in the SSS suture pattern are 10 mm distant to the transected ends of the tendon, incorporate <30% of the cross sectional area of the tendon, and may not significantly interfere with perfusion at the laceration site.

Creating a strong repair and reducing gap formation are very important for successful tenorrhaphy in horses, and other species. Methods to accomplish these ends continue to be improved. Our study shows that a novel repair technique for equine SDFT laceration, the SSS pattern, is significantly stronger and more resistant to failure by tendon pull through than the currently accepted repair technique, the 3LP pattern. The SSS pattern is not less resistant to gap formation than the 3LP in single load-to-failure testing. Further *in vitro* investigation of other key factors such as resistance to cyclic fatigue and effects on tissue perfusion is needed before clinical application can be recommended.

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