Biomechanical analysis of a novel suture pattern for repair of equine tendon lacerations

Eric K Everett

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Jennifer G. Barrett
Nathaniel A. White
Raffaella De Vita

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ABSTRACT

Flexor tendon lacerations in horses are traumatic injuries that can be career ending and life threatening. In the horse, a tendon repair must withstand the strains placed on the tenorrhaphy by immediate weight bearing and locomotion post-operatively. Despite the use of external coaptation, such strains can lead to significant gap formation, construct failure, longer healing time and poor quality of the healed tendon. Similar to equine surgery, gap formation and construct failure are common concerns in human medicine, with early return to post-operative physiotherapy challenging the primary repair. Early return to exercise and decreased gap formation has been shown to reduce adhesion formation. Based on these concerns, the ideal tenorrhaphy suture pattern for equines would provide: 1) high ultimate failure load, 2) resistance to gap formation, 3) minimal alteration in blood supply, and 4) minimal adhesion formation.

Historically, various suture patterns and materials have been evaluated for human and equine flexor tendon repair. Results of equine studies suggest the three-loop pulley pattern (3LP) compares favorably to other patterns and is recommended for primary tenorrhaphy. However, this pattern still experiences significant gap formation and can result in failure. As a result, a technique which decreases the problems inherent in the 3LP is warranted for tenorrhaphy of equine flexor tendons.

A review of the human literature highlights certain characteristics of the tenorrhaphy that may improve results including core purchase length and suture loop characteristics. Optimization of these tenorrhaphy characteristics can increase tenorrhaphy performance and patient outcome. The six-strand Savage technique (SSS) is a pattern routinely used in human hand surgery for tendon repair, and possesses high ultimate failure load and resistance to gap formation that may be beneficial for application in equine tendon repair.

This study compared a novel tenorrhaphy pattern for horses, the SSS, with the currently recommended pattern, the 3LP, in an in vitro model. We hypothesize the SSS will fail at a higher ultimate load, resist pull through, and resist gap formation better than the 3LP.

All testing used cadaveric equine superficial digital flexor tendons from horses euthanized for reasons other than musculoskeletal injury. All testing was approved by the IACUC. The two techniques were applied to cadaveric equine superficial digital flexor tendons. The same investigator performed all repairs (EE). Biomechanical properties were determined in a blinded, randomized pair design. Ultimate failure load, mode of failure and load required to form a 3mm gap were recorded on an Instron Electropuls materials testing system. Gap formation was determined using synchronized high-speed video analysis. Results are reported as mean $\pm$ standard deviation. Statistical comparisons were made using Student's T test, with significance set at $p \leq 0.05$.

The tenorrhaphies were tested for their ultimate failure load and failure mode. The mean failure load for the SSS construct (421.1± 47.6) was significantly greater than that for the 3LP repaired tendons (193.7±43.0). Failure mode was suture breakage for the SSS constructs (13/13) and suture pull through for the 3LP constructs (13/13). The maximum load to create a 3mm gap in the SSS repair (102.0N± 22.4) was not significantly different from the 3LP repair (109.9N± 16.0).

The results of the current study demonstrate that the SSS tenorrhaphy has a higher ultimate failure load and resistance to pull through than the 3LP. The biomechanical properties of the SSS technique show promise as a more desirable repair for equine flexor tendons. However, in vivo testing of the effects of the pattern on live tissue and in a cyclic loading environment is necessary before clinical application of the pattern is recommended.

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Additionally, I would like to thank my wife, Julie, for her undying support and encouragement during the project.

Attributions

Several authors were involved in the project and contributed to conceptualization, execution of the research and production of the thesis.

Jennifer G. Barrett – DVM, PhD Diplomate ACVS (Marion duPont Scott Equine Medical Center, Virginia-Maryland Regional College of Veterinary Medicine) is the primary advisor and committee chair. Dr. Barrett's primary research interest is regenerative medicine and tissue engineering. Dr. Barrett has earned a PhD in molecular biology and has extensive experience in stem cell research. She played a vital role in the overall project design, laboratory work and writing of the thesis.

Nathaniel A. White II – DVM, MS Diplomate ACVS (Marion duPont Scott Equine Medical Center, Virginia-Maryland Regional College of Veterinary Medicine) is a committee member. Dr. White has extensive clinical experience in the treatment of equine tendon and ligament injury. He contributed significantly to the review of the thesis.

Jeffrey D Morelli- BS (Mechanics of Soft Biological Systems Lab- Virginia Polytechnic and State University) Mr Morelli was integral and essential in the design, implementation and execution of the biomechanical testing of the tendon constructs. His academic interest includes exploration and examination of biomechanics in soft tissues, and development of new instrumentation and techniques.

Raffaella De Vita- PhD (Mechanics of Soft Biological Systems Laboratory- Virginia Polytechnic and State University) is a committee member. Dr. De Vita has research interests involving the biomechanics of tendons and ligaments. She contributed significantly to the design and implementation of the biomechanical testing.

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Thesis Organization

This thesis is presented in a format that contains a journal publication as the central portion of the document. The publication is entitled "Biomechanical testing of a novel suture pattern for repair of equine tendon lacerations" and contains its own introduction, materials and methods, results, discussion, and references. The following introduction provides a literature review of tendon repair. The thesis is concluded by final comments that outline future directions for research.

<div align="center">

Chapter 1

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Introduction

Laceration of the flexor tendons in horses is a life threatening and potentially career-ending event. The superficial digital flexor tendon (SDFT) originates on the distal humerus and caudal radius and becomes a tendinous unit at the level of the distal radius. As the tendon courses distally at the level of the metacarpus, it is covered by a very little soft tissue, making it vulnerable to traumatic injury. Flexor tendon lacerations are common injuries that can occur in a variety of ways including kick injuries, lacerations from environmental obstacles and other accidents. Surgical repair of these lacerations is the current recommendation if greater than 50% of the cross sectional area of the tendon is lacerated. The SDFT plays a significant role in locomotion by experiencing a significant load (up to 844 N) and strain (2.2-4.6%)[1], at the walk. This information coupled with the immediate weight bearing required after tendon laceration repair makes equine flexor tendon tenorrhaphy challenging.

Currently the three-loop pulley (3LP) pattern is recommended for repair of equine flexor tendon. The 3LP compares favorably in biomechanical studies by resisting gap formation when compared to a compound locking loop pattern{Easley, 1990 #140}{Jann, 1990 #125}. However, gap formation and construct failure are still common problems observed in equine tendon repaired with the 3LP technique in clinical cases. Interestingly, a similar problem is observed in human flexor tendon repair due to the demands of postoperative physiotherapy to reduce adhesion formation. The demand for increased strength and gap resistance has prompted research into new tenorrhaphy patterns and identification of key elements that influence tenorrhaphy strength.

The goal of this study was to compare a novel tenorrhaphy pattern for equine tendon repair, the six-strand Savage technique, with the currently recommended pattern, the 3LP, in an *in vitro* model.

Flexor tendon anatomy and function

The flexor group of tendons and muscles of the equine forelimb arises from the caudomedial aspect of the humerus. The flexor group is comprised of the *flexor carpi*

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radialis, *flexor carpi ulnaris*, superficial digital flexor and deep digital flexor.[2] The most clinically affected structures are the superficial digital flexor and deep digital flexor. The musculotendinous SDF transitions to a purely tendinous structure at the level of the distal radius where it blends with the accessory ligament of the SDFT. The superficial and deep flexor tendons share a common synovial sheath, the carpal sheath, during their passage through the carpal canal. The SDFT is superficial to the deep digital flexor tendon (DDFT) as it spans the metacarpus, but bifurcates distal to the metacarpophalangeal joint and courses dorsal to the DDFT to insert on the first and second phalanges [2]. The DDFT has multiple originating muscular heads on the humerus, radius and ulna, and is the largest of the flexor group. The tendon passes through the carpal canal and continues down the palmar aspect of the limb to insert upon the palmar surface of the third phalanx. In the proximal metacarpal region, the distal accessory ligament arises from the thick fibrous joint capsule on the palmar aspect of the carpal joint and joins the DDFT in the mid-metacarpal region. This ligament is an important element of the passive stay apparatus and has greater influence than the proximal accessory ligament, which joins the SDFT [3]. As the flexor tendons course over the palmar aspect of the metacarpophalangeal joint they are surrounded by the digital flexor tendon sheath. This synovial environment provides smooth gliding of the tendons as they course over the proximal scutum (intersesamoidean ligament) at the level of the metacarpophalangeal joint.

The blood supply of the flexor tendons arises from their proximal muscular attachments and osseous insertions. Circulation is propagated through the epitenon and paratenon to intertendinous vessels contained within the endotenon. Microradiography studies demonstrate a greater abundance of vasculature around the periphery of tendons[4]. Research conducted on the blood supply of equine SDFT suggests that the tendon has the capability of increasing blood supply during times of injury or exercise, and a flow that approximates that of skeletal muscle[5].

Tendons in the equine forelimb act to transfer muscular forces to articulate and place the limb during locomotion. Specifically, the SDFT works to flex the metacarpophalangeal joint. These tendons contribute to the passive stay apparatus allowing long term weight bearing with minimal muscular effort [2]. During locomotion, the SDFT (coupled with the suspensory ligament) acts as an energy storage mechanism, absorbing and returning elastic energy to the stride. Study of this mechanism has shown the SDFT and suspensory ligament play the predominant roles in the absorption and release of energy [6]. This may be due to the fibrous nature of the musculature that is thought to dampen oscillations during loading rather than provide extensive muscular contraction [7].

Tendon morphology
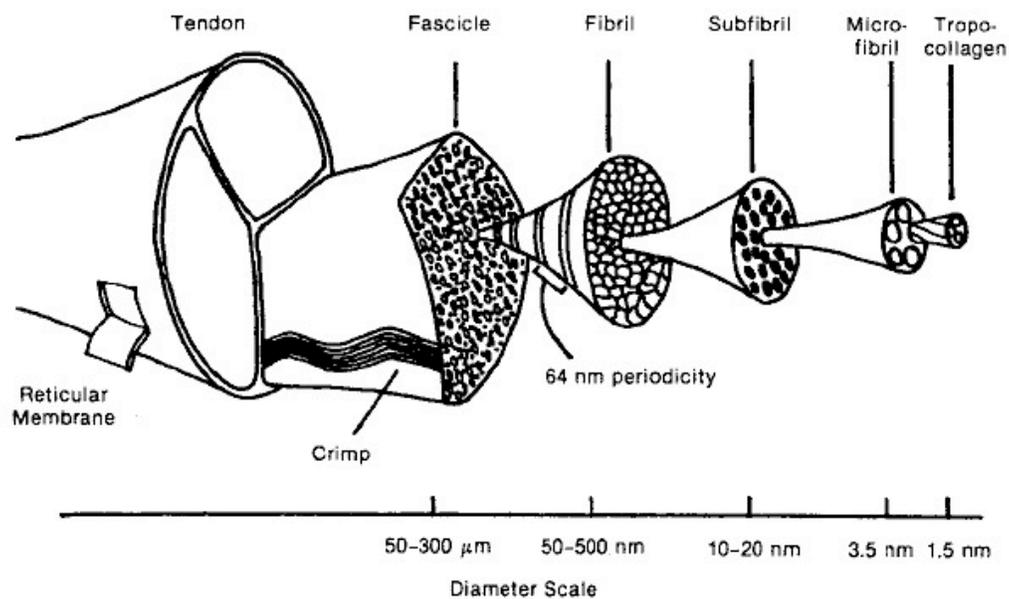

Figure 1: Diagram of collagen bundle hierarchy and internal structure of tendon. (Smith and Schramme, 2003) Used under Fair Use guidelines.

Tendon is a complex tissue composed predominantly of water (70%) and type 1 collagen (30%), along with small amounts of other collagens, proteins and proteoglycans [1]. A longitudinal hierarchical structure is found within tendons composed of decreasing

fiber size (Figure 1). The smallest components are collagen molecules that are joined by intermolecular crosslinks to form collagen fibrils. Fibrils are round in cross section and range from 20-300 NM in diameter. Together, the fibrils form collagen bundles termed fibers by linkages supplied by cytoplasmic extensions of the tenocyte. These fibers ultimately coalesce into groups called fascicles that are visible to the naked eye on cross section. Also visible on cross section is the endotenon, which wraps around fascicles creating tertiary fiber bundles. The endotenon is contiguous with the external surface of the tendon, the epitenon and is an important contributor during tendon stretch as it allows inter-fascicular movement. Endotenon and epitenon are composed of loose connective tissue and contain blood vessels and nerves.

Collagen fibrils are aligned with the longitudinal axis of the tendon, and contain small and large fibril sizes. Studies conducted on the size composition of the fibrils within equine tendon suggests that the fibril size distribution changes with age and growth and is not influenced by exercise or mechanical stress [8]. When collagen fibrils are examined under polarized light, a waveform termed "crimp" is evident (Figure 2). The waveform offers a mechanical "buffer" during the beginning of the loading phase, straightening as the tendon is loaded.
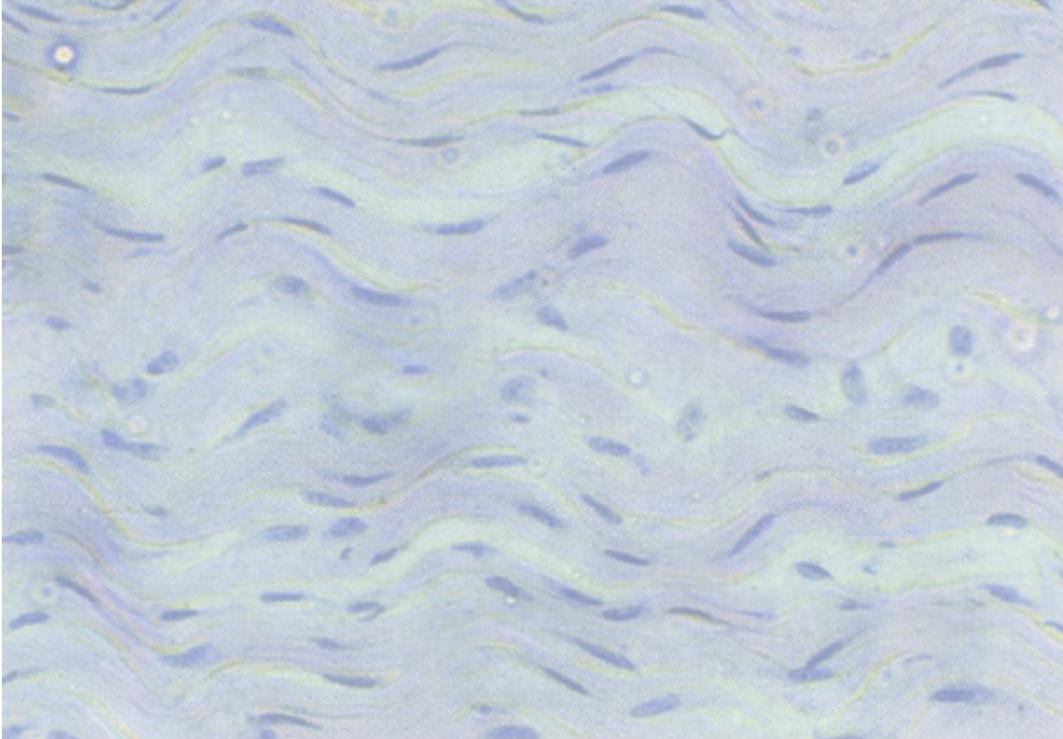
Figure 2: Photomicrograph demonstrating fibril "crimp" waveform. (Smith and Schramme 2003). Used under Fair Use guidelines.

Tendon biomechanics:

Equine flexor tendon is described as a viscoelastic tissue, which indicates a variable stiffness as it stretches during active loading [1,7]. Due to a highly specialized composition and organization, the resultant tendon is a high strength structure able to resist large loads along the axis of fiber alignment. The equine SDFT is able to withstand enormous tensile load before rupture (12,000 N). Strain rates have been measured *in vivo* for equine flexor tendons and approximate 3-8% at the walk, 7-10% at a trot, and 12-16% at a gallop [9,10]. Elongation past 20% of their length will cause rupture with irreversible damage occurring between 16-20% elongation, such that equine flexor tendons operate close to their functional limit during exercise [5].

Standard load displacement curves can be developed during *in vitro* testing of tendon and tenorrhaphy techniques (Figure 3). Similar to a stress-strain curve, the load displacement curve shows behavior of the tissue as biomechanical forces are applied. The

toe region of the curve demonstrates stretch as the tendon is loaded and crimp is straightened. As loading continues the relationship becomes linear with a more uniform response to load and is used to define the stiffness of the tendon or construct being tested. Finally as the load values peak, a yield point is reached where failure of the tissue or tenorrhaphy fails.
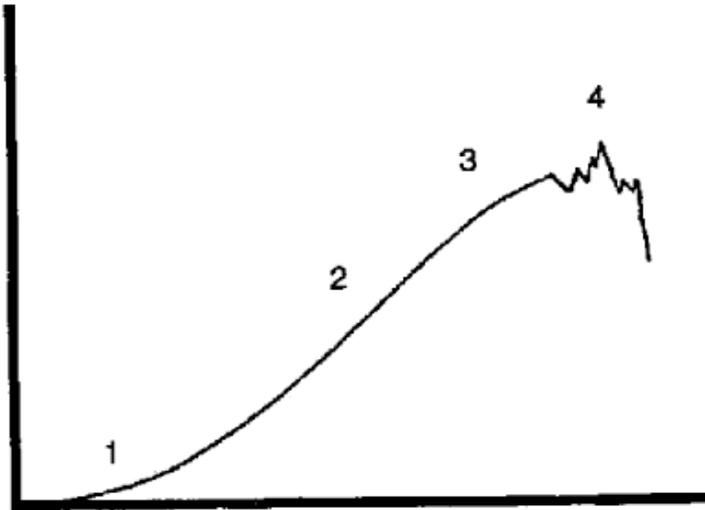
Figure 3: Load displacement curve, adapted from Dowling and Dart 2005. Key: 1, toe region; 2, linear region; 3, yield point; 4, rupture. Used under Fair Use guidelines.

Pathophysiology of tendon healing

After injury to tendon tissue, the inflammatory stage of healing begins. Intratendinous hemorrhage in the area of tissue damage is quickly followed by the development of edema within the tissue and migration of neutrophils, macrophages and monocytes. The inflammatory response in horses appears to be exaggerated with additional tissue damage occurring after the release of proteolytic enzymes released to remove necrotic tissue [5]. The inflammatory stage occurs from day 0 until day 7-10. Following the inflammatory stage, the healing process shifts to the reparative phase, which predominates between days 14 and 45 and consists of angiogenesis and infiltration of fibroblasts. Over the following months, scar tissue is formed with an increased content of type III collagen and glycosaminoglycan [11]. At the completion of

scar tissue formation, the remodeling phase begins around day 60, which attempts to convert the collagen content from type III to predominantly type I. This process is often incomplete, resulting in a tendon tissue that is strong, but has decreased elasticity compared to normal tendon [12].

When injury occurs within a tendon sheath, the process is similar, but less efficient due to the lack of a paratenon and its role in tendon healing. The intrinsic capabilities of the tendon to heal (from the endotenon) appear to be limited [5]. Additionally, the presence of synovial fluid and sepsis from the laceration within the tendon defect is thought to cause retardation of the healing process[13].

Review of human tenorrhaphy biomechanical studies

Introduction

An area of active research in human orthopedics is the primary repair of flexor tendon lacerations to the hand [14-17]. The primary goal for repair of these tendon injuries is flexibility and gliding [18,19], reduction of adhesion formation[20-23], and preserving function. Adhesion formation after laceration to the flexor tendons causes decreased manual dexterity and reduces manual functions such as writing and instrument use [14-17]. Early return to passive range of motion has been recommended to reduce adhesion formation[24]; however, gap formation can occur during this therapy, reducing the quality of the healed tissue and further restricting motion [14,20,25]. Because active or combined passive and active finger motion is increasingly recommended in postoperative treatment regimens, investigations have focused on increasing strength of the tendon repair to resist gap formation [26].

In order to achieve the most desirable outcome, the ideal tenorrhaphy suture pattern would provide: 1) a strong repair 2) minimal gap formation and 3) minimal adhesion formation. Previous *in vitro* and *in vivo* studies in human cadavers and animal models have identified the properties of tenorrhaphy that contribute to these qualities. Important variables identified include core purchase length [27,28], strand number and size, [29-31] and grasping *versus* locking attributes [26].

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Core purchase length

Length of suture purchase is defined as the exit or entry distance of the core suture from the cut end of the tendon [32]. This effect of this property on the strength of the repair is related to obliquely oriented and transversely oriented lacerations. In obliquely transected tendon, the main effect of core purchase length is to increase overall construct strength by moving the suture-tendon interface a greater distance from the transection site [32]. Studies to optimize the core purchase distance between grasping and non-grasping patterns [27], and grasping and locking patterns [33] identified the ideal purchase length to be 7-10mm from the cut edge. At this distance, resistance to the formation of a 2mm gap and the ultimate strength was the highest. In addition, Cao *et. al.* demonstrated that when using a non-grasping pattern, core purchase length is a vital consideration to optimizing strength{Cao, 2006 #174}. These authors found that repairs completed with a 4mm core purchase regularly failed by suture pull through, in contrast, the same repair with a 10mm core purchase failed by suture breakage.

Suture strand number

Multiple studies examining multi-strand repairs found that the number of strands crossing the laceration creates a stronger repair [34-39] Increased strength may be attributed to increased material strength, as well as the number of separate grips in the tendon stroma [40]. Many of these studies employed multi-strand core suture patterns in static pull to failure testing. Patterns tested include two strand Pennington, two strand Tajima, four strand cruciate, four strand Kessler, six-strand Savage, and even an eight-strand method [41]. While ultimate failure load and gap [42] resistance appears to be increased during *in vitro* testing, application of multistrand repairs *in vivo* has been questioned [43]. Application of these patterns is typically to small flexor tendons of the human hand or finger, which require gliding function with little increase in bulk to avoid "triggering" through tendon pulleys. Hirpara et. al. found that when examining a core pattern with 6 strands (six-strand Savage) the increased bulk was not sufficient to increase the work of flexion, and was significantly stronger compared to 2 or 4 strand repairs{Hirpara, 2007 #167}. However, other authors [18,40,44] showed that all repairs increase the work of flexion, and do so by the presence of suture loops and knots on the surface of the tendon.

Gap formation also has an important influence on the work of flexion [45] and should be minimized to produce an acceptable result. Increasing gap resistance required using double stranded [46] and triple stranded versions of the above mentioned patterns. These patterns did result in increased ultimate strength, stiffness and resistance to gap formation when compared to single stranded multi-pass techniques with the technical demands of a two stranded technique [40]. However, further research on gliding resistance and tendon healing with multistrand repair are needed. A balance between qualities of ultimate strength and resistance to gap formation obtained while considering the clinical complexity of application and work of flexion to provide an optimal repair.

Suture material and size

Suture material chosen for flexor tendon repair has been on the basis of minimal tissue reaction, retention of strength, handling and knotting characteristics, and low extensibility [47]. Historically, common choices in human tenorrhaphy have been braided polyester, nylon, and monofilament polypropylene. Retention of tensile properties by braided polyester is superior to nylon or monofilament polypropylene[47-49]. A newer material, braided polyblend polyethylene (Fiberwire), has increased ultimate strength and stiffness when compared to traditional choices, and a similar ultimate strength and higher stiffness than stainless steel [49,50]. A commonly used suture size in many of the human biomechanical tests is 3-0 USP. Studies comparing 3-0 USP to 4-0 USP have concluded that the ultimate tensile strength of the smaller suture is less than the holding capacity of the tendon for several locking and grasping patterns [31,33,51,52]. Using a larger suture size improves the ultimate strength in static testing, but does not increase the yield point or gap resistance [16,53].

Grasping v. *Locking attributes*

There has been much debate and confusion regarding the use of the terms 'locking' and 'grasping' in the tendon repair literature. The terms are used interchangeably in the literature to describe the configuration of suture loops utilized to capture tendon fibers and gain purchase in the tendon [29]. The relationship of the transverse leg and the longitudinal leg of the suture as it forms a loop helps to distinguish

the two types (Figure 4) but is not a conclusive classification for many patterns. A loop is considered locking if it tightens around fiber bundles when the suture ends are under tension, shown by "B" in Figure 4. Conversely, if the loop pulls through the fiber bundles when tightened, the loop is termed a grasping loop [29], demonstrated by "D" in Figure 4. Other authors [40,52] propose the locking group be subdivided into circle-locks and cross-locks based on their interaction with the tendon fibers. Biomechanical studies show the benefit of direct grip on tendon fibers yielding higher ultimate strength and lower gap formation [29,31,46,54,55]. The size of the loop engaging the tendon fibers has also been shown to influence biomechanical performance. When the cross sectional area of each loop is approximately 15% of the cross sectional area of the tendon when using a Pennington suture pattern, the ultimate strength was optimized [54]. Further increases in cross sectional area of the loop appear to promote gap formation [54]. When a cruciate pattern was employed the cross sectional area of 25% yielded the best biomechanical performance [56].
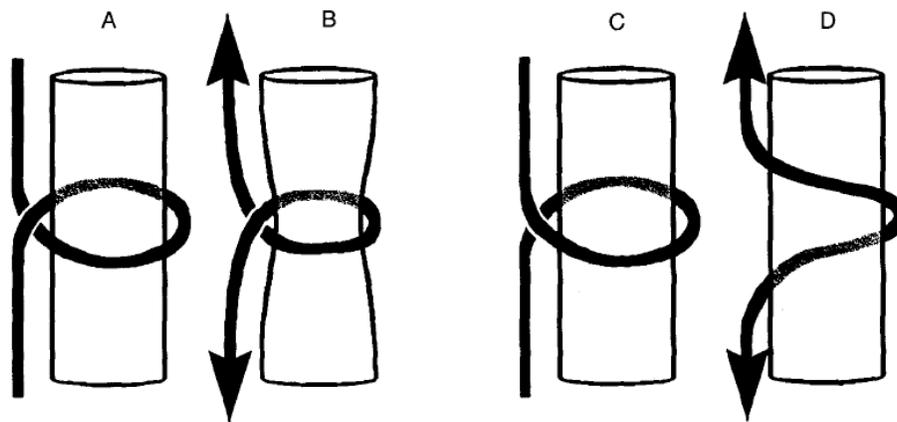
Figure 4: Locking *v*. Grasping loop configuration. (Hotokezaka and Manske 1997). A and B show a locking suture loop surrounding tendon fibrils before and after tension application. C and D demonstrate a grasping loop's interaction with tendon fibrils before and after tension application. Used under Fair Use guidelines.

Savage (1985) initially described a new six stranded technique for repair of human digital flexor tendons in an effort to improve the tenorrhaphy strength and

therefore its ability to withstand early mobilization therapy. Since that time, the pattern has been routinely employed in human hand surgery, and has compared well biomechanically with other patterns [26,39,46,53,57]. The pattern employs a number of crossing loops in a cruciate fashion (Fig 5), effectively securing tendon fibrils within the repair on both sides of the laceration. The pattern's ability to resist gap formation[26,46,58], with high tensile strength[33,37,39,57,58] and smooth gliding function[14,18] favor its use .
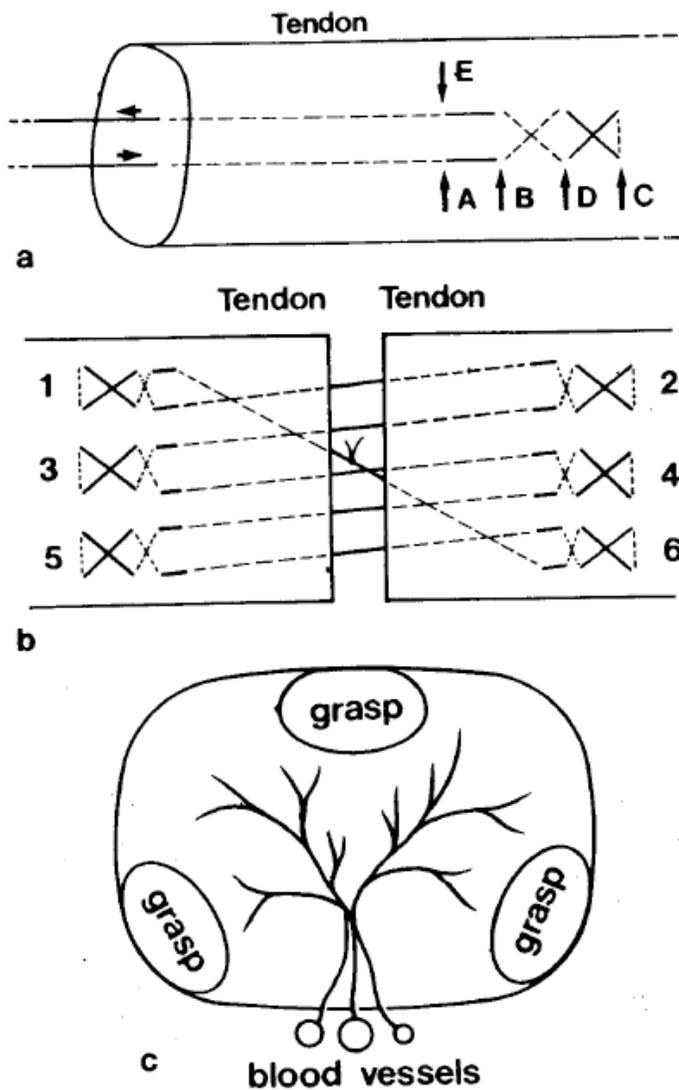
Figure 5: Diagram of six-strand Savage technique (Savage and Risitano 1989). Used under Fair Use guidelines.

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Clinical Significance of Equine Flexor Tendon Laceration:

Lacerations involving the digital flexor tendons in horses can be both career and life-threatening [59-62]. These injuries have a variable prognosis for return to athletic performance. Case reports from the 1980s and 1990s indicated a poor prognosis for return to function with only 11-18% of cases [61]. Subsequent reports provided a fair prognosis for return to use at 59% [59], and 55% [63], though requiring lengthy convalescence for healing. Primary reconstruction of lacerations is recommended in horses to provide a better prognosis for return to activity [60], though many difficulties are present to achieve this end.

Along with a protracted convalescent period, limited healing capacity of equine flexor tendon, and demanding biomechanical role of the SDFT, surgical repair after traumatic laceration is challenging. In addition to loss of tissue from traumatic injury making apposition of tendon ends difficult, tenorrhaphy of the SDFT is prone to gap formation [60,62,64,65]. Currently recommended tenorrhaphy techniques frequently result in gap healing with excessive scar formation and frequent construct failure despite reduction of strain with external coaptation [60,62]. Due to the aforementioned problems, the development of a strong repair that minimizes gap formation is crucial to the improvement of treatment of flexor tendon lacerations in horses [13,25,62,64].

Review of equine flexor tenorrhaphy literature

Tenorrhaphy patterns

A variety of suture patterns and techniques have been evaluated in the horse [62,66,67]. Although a number of studies of tenorrhaphy have been performed, an ideal suture technique for repair of flexor tendon lacerations has not been identified [62,67,68]. Early attempts at re-apposition of severed flexor tendons in horses centered on using a single locking loop pattern [66] adapted from the Kessler tenorrhaphy used in human patients. This pattern is created by passing the suture material parallel to the tendon's long axis

followed by placing the suture perpendicular to the long axis thereby encircling tendon fibrils. The locking loop pattern has the reported advantages in ease of placement with little inhibition of intrinsic tendon microvasculature [69]. Further examination of this pattern demonstrated an inability of the pattern to maintain apposition of the tendon ends in weight bearing horses with the distal limb immobilized in a cast [65]. The three-loop pulley pattern is applied via 3 successive loops that are offset by equal distances around the circumference of the tendon (Figure 6). Due to the non-locking nature of the suture passes, the pattern relies on collagen cross-links between the fascicles for holding strength. This pattern has been commonly used for both equine and small animal tendon repair.

Biomechanical studies have compared one, two and three locking loops with a three-loop pulley pattern in static pull to failure testing [66]. With the addition of more locking loops, and suture strands crossing the laceration there was improvement in the strength of the constructs. Gap formation was less with the triple locking loop than the double or single locking loop, and would fail at approximately 33kg of force [66]. When the locking loops and three loop pulley were compared for strength the three loop pulley was as strong as or stronger than the other patterns. Gap formation was improved with the three-loop pulley for static tests, and comparable to the locking loop in dynamic tests. Failure mode of the three-loop pulley was exclusively via suture pulling through the tendon. In contrast, the locking loop sutures failed by suture breakage the majority of the time. The single locking loop pattern and three-loop pulley were also evaluated using differing strand numbers passed simultaneously alone or braided together to form a "cable"[67]. The study concluded that the strength of the repair was improved with greater suture strand numbers, however, the resistance to gap formation was much poorer than for a single strand approach [67].

Conservation of blood supply to healing tendon has been recognized as an important tenant of tendon repair but few studies to evaluate perfusion after tenorrhaphy have been completed. Study of the superficial digital flexor tendon of horses has revealed a complex vascular system [70], and disruption of this system would presumably have deleterious effects to the healing process [71]. A study completed by Crowson *et al.* compared the locking loop pattern to the three-loop pulley pattern during terminal

experimental tenotomy procedures. Microangiographic analysis of serial transverse sections of repaired tendons were used to quantify blood supply to the tissues following tenorrhaphy, by assessing regional perfusion with barium sulfate following tensioning of the tenorrhaphy. Results of the study suggested the three-loop pulley is less restrictive to blood flow than a locking loop pattern, though greater than control segments.

Suture material

The ideal suture material for repair of tendon lacerations has received considerable attention in both the veterinary and human research fields. Desirable qualities for this suture are; absorbable with low tissue reactivity, high initial strength, strength retention for an adequate period of time, and good knot retention. Monofilament nylon, carbon fiber, and polydioxanone suture material have been the predominant types used in equine repairs. Monofilament nylon has been chosen due high tensile strength, long duration of tensile strength, minimal tissue reaction and anti-bacterial properties upon degradation [5,62] and has been used *in vitro* for biomechanical testing of tenorrhaphy patterns [62,66]. Initial work with carbon fiber suture was encouraging [72,73] because investigations found it might serve as a scaffold for fibroblast migration [62] in a gap-healing model. However, subsequent appositional studies demonstrated a foreign body response, even with a coating of poly l lactic acid, and resulting in a repair with lower mechanical strength than nylon [65]. Polydioxanone (PDS) is a synthetic monofilament absorbable suture that has been recommended for tenorrhaphy and has been used in multiple *in vivo* studies [13,63,68,74] in animals for tenorrhaphy. The suture has been reported to retain 86% of its tensile strength at 8 weeks [75].

Other methods

Other forms of equine flexor tendon repair have been reported including plating with absorbable poly-l-lactic acid (PLA)[74], stainless steel [76], autologous grafting [68] and the use of a bio absorbable implant [77]. Plating equine deep digital flexor tendon with PLA was able withstand 38% of load placed on the tendon at the walk [74]. This study also compared the plated tendon repair to the 3LP, finding a significant increase in ultimate strength with the plated repairs (1563 +/- 100.4 for plated repairs, 458.9 +/- 63 N for

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3LP). The mode of failure was suture breakage for the plated repairs and suture pull through for 10/12 sutured repairs, with the remaining two failing by suture breakage. The study used 2 polydioxanone in each repair, though core purchase length and other variables did not appear to be controlled in this study. Another plating study that utilized Stainless steel plates was found to support a load of 406.2N +/- 69.6 [76]. These plates were secured to the end of the plate and the tendon with 2 polypropylene sutures in a locking loop pattern. A three, four or five locking loop sutures were used on each plate end, with no significant difference observed between 3 and 4 or 4 and 5 sutures per plate end. 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 is unknown.

Other approaches to re-apposition of the severed tendon ends and promoting re-union have been reported. The use of an autogenous graft, harvested from the lateral digital extensor tendon was described and evaluated [68]. The grafts were secured using a locking loop pattern of 2 polydioxanone. Control repairs were conducted on the contralateral limb with a locking loop pattern of 2 polydioxanone. The repairs were harvested from the both limb for histologic and biomechanical testing after euthanasia at set time points. This study found the repair strength to be greatest in the grafted repairs at 6 and 12 weeks. At 24 weeks the two repairs had comparable biomechanical properties. The histology of the grafted tendons appeared more mature and organized than the sutured repairs at 12 weeks.

A different approach, utilizing a woven bio absorbable implant [77], can applied when there is significant tissue loss. Four clinical cases in which an implant of poly-L lactic acid was used to provide stability and a scaffold between retracted tendon ends after laceration.[77] The implants were made of 13 strands woven into a flexible implant. Fixation of the implant in each case was different and no biomechanical testing was conducted. The implants used in four horses appeared to be well tolerated and two horses were sound at follow up after one year. The remaining two horses had mild persistent lameness and were not in use. Polypropylene implants were used in another case report [78] to successfully repair a deep digital flexor tendon laceration with substantial tissue loss. The implants were 1.5mm thick and 8mm wide used as a pair and secured to the tendon

using polydioxanone in a simple interrupted pattern. The horse was reportedly sound and in use at follow up 2 years post-operatively.

Gap healing

Gap healing occurs as a result of failure or slippage of a construct, or during conservative treatment of flexor tendon lacerations. when cast application is used alone and tendon ends are not apposed, healing is slower with a lower histologic quality to the healed tissue [60,62]. Histology completed on experimentally created tendon lacerations, which were subsequently sutured, demonstrates a higher level of tissue organization earlier in the course of healing than without tenorrhaphy. Also, a more rapid increase in strength at the injury site has been demonstrated after biomechanical testing of these tendons.

Conclusions

The development of a strong repair that minimizes gap formation is crucial to the treatment of flexor tendon lacerations in horses[13,25,62,64]. Although a number of studies in horses have been performed, an ideal suture technique for repair of flexor tendon lacerations has not been identified [62,67,68]. In order to achieve the most desirable outcome, the ideal tenorrhaphy suture pattern would provide: 1) a strong repair 2) minimal gap formation and 3) minimal adhesion formation. Results of previous studies suggest the three loop pulley (3LP) compares favorably to other patterns, such as the compound locking loop (CLP), and has been recommended for primary tenorrhaphy in the horse [66]. However, the low ultimate failure load of the 3LP pattern (31.5 kg ± 4.0) and failure by pulling through the tendon rather than suture failure suggests that tenorrhaphy technique for equine flexor tendons lacerations can be improved.

A review of the human flexor tenorrhaphy literature highlights the use of suture patterns such as the six-strand Savage technique, which utilizes a grasping mechanism in order to engage tendon fibrils in the longitudinal axis for greater strength. In contrast, the 3LP pattern relies on collagen cross-linking and other inter-fibril connections to resist suture pull through, as it is neither a grasping nor locking pattern. Application of a

technique such as the six-strand Savage, offers beneficial biomechanical properties that could be advantageous for application to equine patients.
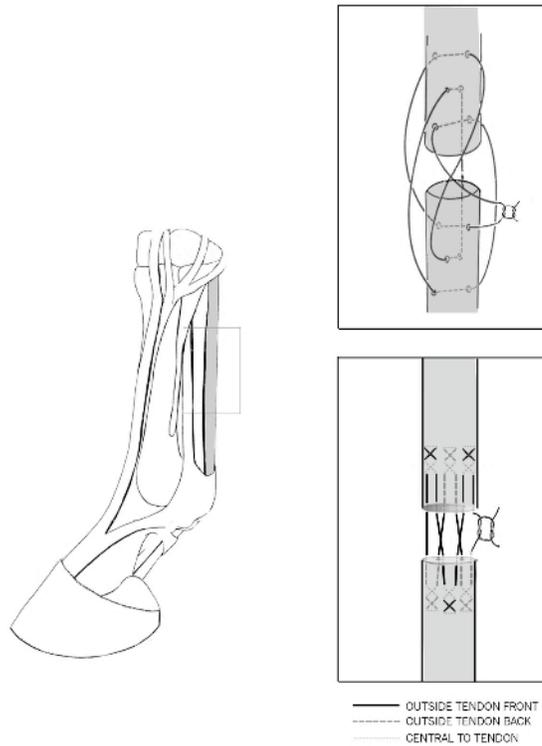

Figure 6: Three loop Pulley (top) and six strand Savage technique (bottom). (art work courtesy Jeremy Everett)

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Chapter 2

BIOMECHANICAL ANALYSIS OF A NOVEL SUTURE PATTERN FOR REPAIR
OF EQUINE TENDON LACERATIONS.

Eric K Everett, MS, DVM[1], Jennifer G. Barrett, DVM, PhD[1*], Jeffrey Morelli, BS[2],
Diplomate ACVS, Raffaella De Vita, PhD[2]
[*]Corresponding Author

Abstract:

Objective: To compare *in vitro* biomechanical properties of a novel suture pattern to the current standard for primary repair of equine superficial digital flexor tendon (SDFT) laceration.

Study Design: *In vitro*, blinded, randomized paired design.

Animals: 24 cadaveric equine forelimb SDFTs.

Methods: The three-loop pulley (3LP) and six-strand Savage (SSS) suture patterns were applied to transected equine superficial digital flexor tendons. Ultimate failure load, stiffness, mode of failure and load required to form a 3mm 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 $p \leq 0.05$.

Results: The SSS repair failed at a higher ultimate load (421.1N± 47.6) than the 3LP repair (193.7N± 43.0). There was no significant difference in stiffness. Failure mode was suture breakage for the SSS repair (13/13) and suture pull-through for the 3LP repair (13/13). The maximum load to create a 3mm gap in the SSS repair (102.0N± 22.4) was not significantly different from the 3LP repair (109.9N± 16.0).

Conclusions: This study demonstrates that the SSS tenorrhaphy has improved strength and resistance to pull through than the 3LP when applied to equine SDFTs in a single load to failure test. Loads required to form 3mm gaps were not significantly different between SSS and 3LP.

Clinical Relevance: The biomechanical properties of the SSS technique indicate that it is a stronger repair for equine flexor tendons. However, cyclic testing and *in vivo* healing studies are warranted prior to recommending clinical use.

KEYWORDS: Equine, Tenorrhaphy, Biomechanics, Tendon, and Laceration

Introduction:

Lacerations involving the digital flexor tendons in horses are traumatic injuries that can be both career and life-threatening [1-4]. These injuries have a poor prognosis for return to athletic performance, with a variable percentage (18-51%) of horses returning to their previous level of performance [1,3]. Primary reconstruction of lacerations is recommended in horses to provide a better prognosis for return to activity [2].

The superficial digital flexor tendon (SDFT) is integral with the, deep digital flexor tendon (DDFT) and suspensory ligament in supporting the metacarpo/tarsophalangeal joint in a specific conformational orientation above the ground. These tendons and ligaments absorb shock and store elastic energy during motion, and contribute to weight bearing in the standing horse [5]. Even during minimal exertion such as walking, the superficial digital flexor tendon experiences load as high as 3559 N (363 kg), and strain of 2-5% [6-10].

Anatomically, the SDFT is the more commonly lacerated, due to its superficial location on the palmar/plantar surface of the limb (Figure 1). 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 making apposition of tendon ends difficult, tenorrhaphy of the SDFT is prone to gap formation after the limb is weighted. 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]. Due to the aforementioned problems, the development of a strong repair that minimizes gap formation is crucial to the treatment of flexor tendon lacerations in horses [4,11-13].
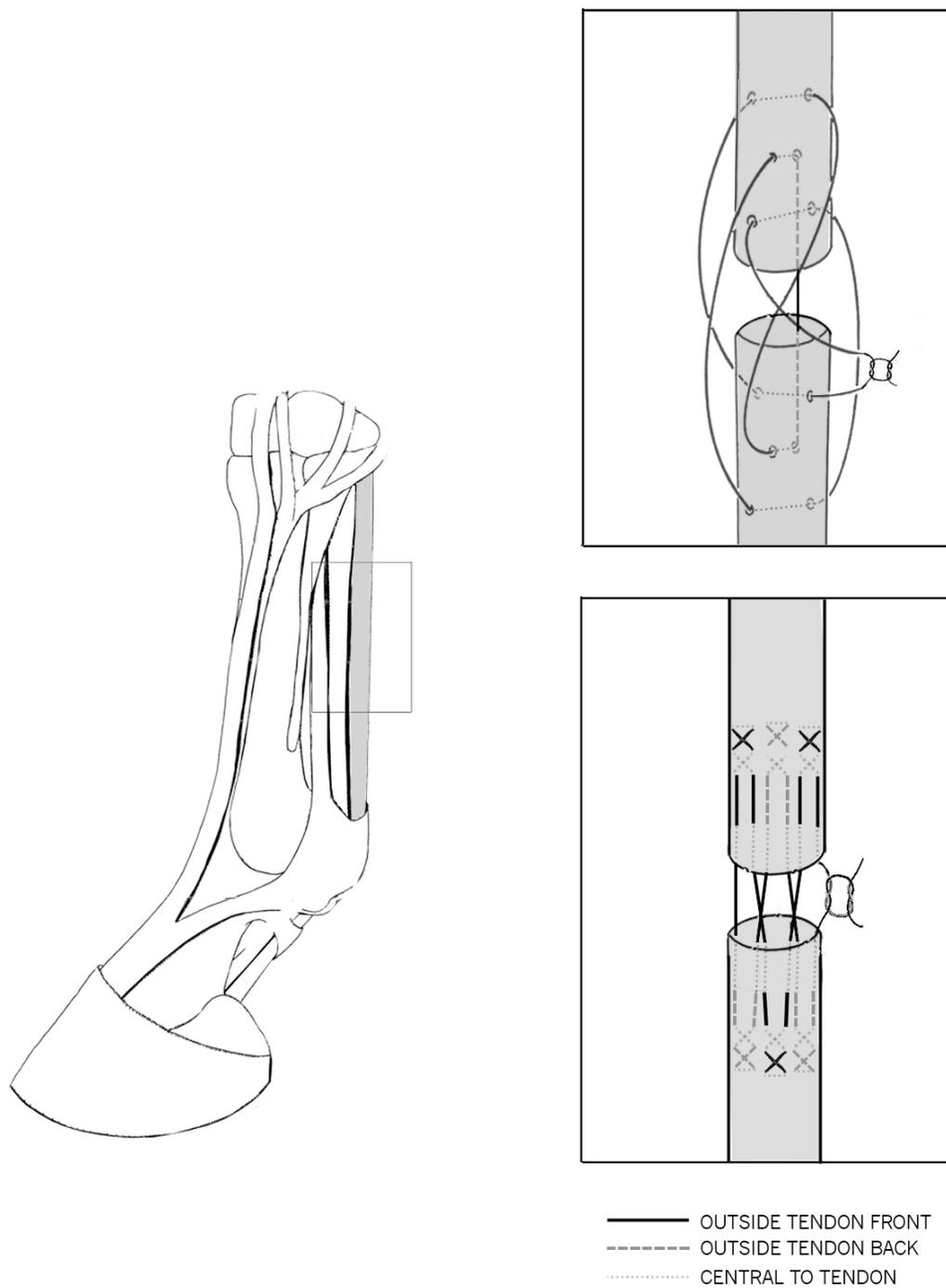
Figure 1: Diagram of equine distal limb illustrating flexor tendon anatomy, region of tendon used in repairs and tenorrhaphy patterns used six strand savage (bottom) and three loop pulley (top).

Although a number of studies in horses have been performed, an ideal suture technique for repair of flexor tendon lacerations has not been identified [4,14,15].

In order to achieve the most desirable outcome, the ideal tenorrhaphy suture pattern would provide 1) a strong repair 2) minimal gap formation and 3) minimal adhesion formation. 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 [16,17], strand number and size, [18-20] and grasping *versus* locking attributes [21]. While studies of human flexor tendon reconstruction focus on a strong repair to withstand post-operative physiotherapy [22-24], a repair with similar qualities is desired in equine surgery to endure the strains placed on the repair during post-operative weight bearing.

Historically, a variety of suture patterns and techniques have been evaluated in the horse [4,14,25]. Results of these studies suggest the three loop pulley (3LP) compares 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 kg ± 4.0) and failure by pulling through the tendon rather than suture failure suggests that tenorrhaphy in equine flexor tendons can be improved.

The six-strand Savage technique (SSS) is routinely employed in human hand surgery for tendon repair, and has compared well biomechanically with the 3LP in other species [21,26-29] The SSS utilizes a grasping mechanism in order to engage tendon fibrils in the longitudinal axis for greater strength. In contrast, the 3LP pattern relies on collagen cross-linking and other inter-fibril 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 two patterns, focusing the investigation on the intrinsic qualities of the tenorrhaphy under load.

The goal of this study was to compare a novel tenorrhaphy pattern for equine tendon laceration repair, the SSS technique, with the currently recommended pattern, the 3LP, in an *in vitro* model. We hypothesize 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 hypothesize that failure mode for the SSS will be primarily by suture breakage, and the 3LP will fail primarily by suture pulling through 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 blinded, randomized design. Comparisons were made using randomly assigned, paired tissue samples from each horse: a 3LP was performed on one forelimb, and a SSS on the contralateral limb. The same surgeon performed all tenotomies and tenorrhaphies to ensure consistency. The same suture - #2 polydiaxanone - was used, in a six-strand continuous pattern for each, meaning that the suture crosses the tenotomy site 6 times. Identical bites were made 5mm from transection site, and identical core purchase lengths were used. The ultimate failure load, stiffness, mode of failure and the load required to create a 3mm gap were computed by performing tensile tests.

Sample preparation

Pairs of forelimb superficial digital flexor tendons were collected from 12 adult horses euthanatized for reasons other than musculoskeletal injury. The horses consisted of 5 Thoroughbreds, 2 Warmbloods, 1Warmblood cross, 1Thoroughbred cross, 1Arab, 1Quarter Horse cross, and 1 Draft cross. The horses had an average age of 12 (range: 2-25 years old) and consisted of 7 geldings and 5 mares.

The flexor tendon specimens were isolated in the metacarpal region from a point immediately distal to the carpal canal to a point adjacent to the apex of the proximal sesamoid bones. The flexor tendons 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, Baxter Healthcare Corp, Deerfield, IL, USA) material and sealed in plastic before freezing. The tendon specimens were preserved at -70º C until they were transported frozen on dry ice to the testing laboratory.

After thawing to 30ºC, 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 identical 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 ½ x 40mm cutting needle (PDS, Ethicon Inc, Somerville, NJ, USA). The tissue was kept moist by repeated application of saline during the preparation of all specimens. 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 5mm from the transected ends, and incorporating 20mm core purchase length from the transected tendon ends for each suture pattern. Additionally, the tendons were marked 5mm 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 tenorrhaphy sutures were tightened and tied 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, USA), with a load cell of static capacity of +/-710 N was used to perform tensile tests on the tendons (Figure 2A). Custom-designed cryogrips were used to secure the specimens for testing and were engineered from 6061 aluminum to avoid slippage (Figure 2B).

Figure 2A and 2B: Materials testing machine and tendon grips.

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, USA). The cryogrips immediately froze to each end of the tendon specimen and the test was immediately performed. The samples were placed under preload (1N) before commencing the test, and load data was collected every 8 ms during the test. The experiments were conducted in load control at 25mm/sec until failure occurred. Failure was defined as either suture breakage or pull through. Load at failure was recorded in Newtons (N) and mode of failure 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, USA) synchronized with the material testing system load cell data collection software (BlueHill 2, Instron Inc, Norwood, MA, USA). Specifically, markers on the surface of the specimens and the ends of the tendons were tracked using high-speed videography (125fps). Videographic analysis software (ProAnalyst, Xcitex Inc, Cambridge, MA, USA) 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 30º C. The tensile load that induced 3 mm gap formation was determined using the ProAnaylst software. By plotting the load versus elongation of the specimens, a nonlinear load-elongation curve was obtained for each tenorrhaphy (Figure 3A and Figure 3B). Stiffness was determined using the slope of the linear region before the yield point of the load deformation curve.
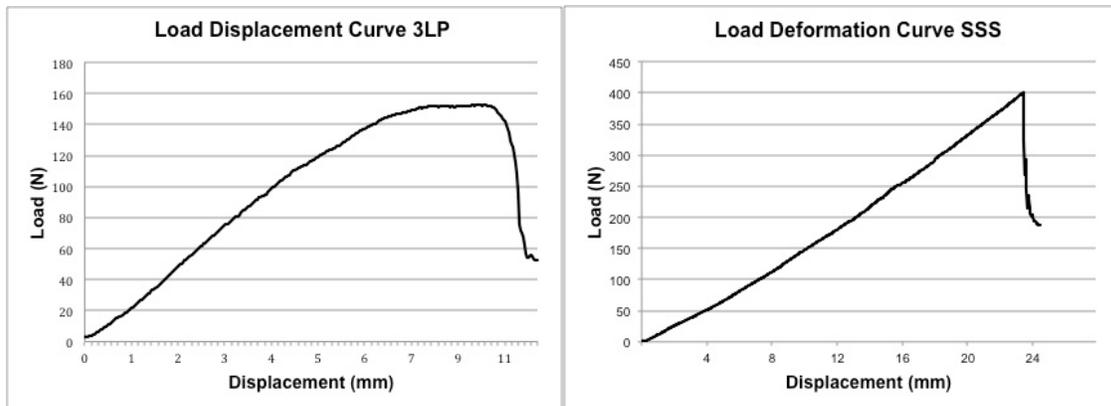
Figure 3A and 3B: Load elongation curves for tenorrhaphies using the 3LP and SSS suture patterns.

Data analysis

Statistical analysis was performed using SAS JMP 8 (SAS Institute, Cary, NC, USA) and StatPlus v5.7 (AnalystSoft, Vancouver, BC, Canada). The data from all tendons were included in descriptive statistics and statistical analyses. Data are reported as mean ± standard deviation. Biomechanical data comparing the tenorrhaphy patterns were analyzed pair-wise using Student's *t*-test. Significance was set at $p \leq 0.05$.

Results:

The ultimate failure load, mode of failure, and stiffness data for the SSS and 3LP are presented in Table 1. A comparison of the load for mean gap formation for the two tenorrhaphy patterns is represented in Table 2. No grip failure or slippage occurred during testing.

Load at construct failure, failure mode and stiffness

The ultimate failure load (mean ± SD) for the SSS repair (421.1N± 47.6) was significantly higher than the 3LP repair (193.7N± 43.0) (P<0.001). Failure mode was suture breakage for all SSS repairs (13/13) and suture pull-through for all 3LP repairs (13/13). Stiffness of the SSS repair (19.5± 2.3) was not significantly different than the 3LP repair (19.4 ± 4.6).

Load at 3mm gap formation

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

Discussion:

This study compared biomechanical properties of two six-strand suture patterns using paired equine SDFT cadaver specimens. The results support the conclusion that the SSS suture pattern withstands a significantly greater maximum load prior to failure than a 3LP pattern in equine superficial digital flexor tendons, *in vitro*.

Our results do not demonstrate a significant difference in resistance to gap formation between the two tenorrhaphy patterns. This was surprising considering that the 3LP exclusively failed by pulling through the tendon tissue. Our hypothesis was that the grasping SSS pattern would be more resistant to gap formation, since we suspected gap formation occurred during suture pull through. One explanation for this result is that 3mm gap formation occurred through stretching of the suture material in both suture patterns. This would explain the similar loads at which the 3mm gap formed.

Due to low tensile strength of the traditional tendon repair relative to the forces placed on the tendon immediately post-operatively, casting of the metacarpophalangeal joint in slight flexion has been standard practice following flexor tendon 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 [6]. Our data suggests that the 3LP suture pattern repair is capable of supporting approximately 5% of the load placed on the SDFT before construct failure occurs. In comparison, the SSS is able to support greater than twice the load experienced during walking before failure (12%). While external coaptation would still be necessary during the early convalescent period, the increase in tensile strength offered by the SSS suture pattern 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 flexor tendon repair have been reported including application of plates made of absorbable poly-l-lactic acid (PLA) [30] and stainless steel [31]. Equine deep digital flexor tendons repaired with a PLA plate withstood 38% of load placed on the tendon at the walk (1507.08N ± 184.34). Stainless steel plates supported a similar load (406.2N ± 69.6) [31] to that demonstrated for the SSS in this study. Although strong, plating for tendon repair incorporates 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 is unknown. Direct comparison of ultimate failure load from these studies is not possible, due to differences in cross sectional area of the tendons (SDFT v. DDFT) as well as differences in strain rate during testing.

Gliding function and early strength for mobilization therapy are important in human hand surgery, and has been studied extensively using a variety of suture patterns [32-34] and adhesion prevention strategies [35-38]. For horses, it has been suggested that the 3LP might inhibit gliding [14] due to 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 flexor tendon sheath [39]. Due these risks, a suture pattern like the SSS that possesses increased strength [40] and low adhesion formation [41] is desirable.

Historically, many suture materials of different sizes have been used in equine tenorrhaphy studies including monofilament nylon, polypropylene, polydioxanone, carbon fiber, and poly-L-lactic acid. An ideal suture material for tenorrhaphy would be non-inflammatory, strong throughout the healing period, and absorbable, and would possess low tissue drag. Polydioxanone (2 USP) was chosen for this study because of its ability to meet the aforementioned criteria, retaining 86% of its strength at 8 weeks [42]. Additionally, this material has been used in previous equine tenorrhaphy studies, and has been suggested to be an appropriate suture type for *in vivo* equine flexor tendon repair [14].

The length of core suture purchase [43] and strand number [18-20] within the tendon are important contributors to tenorrhaphy strength. Experimental models using porcine tendon have shown the ideal core suture purchase length to be between 7mm and 10 mm from the edge of the laceration [16,44]. Comparable studies in equine cadaver tendon have not been performed; however, keeping this factor identical between the two suture

patterns should control for this variable. A greater number of suture strands crossing the laceration will produce a stronger repair, but can create excess bulk and also increase surgery time [29,45]. When suture strand number is kept constant between patterns, the intrinsic qualities of the pattern will influence the biomechanical properties of the repair [21]. In order to compare the intrinsic qualities of the 3LP and SSS, our study used standardized suture bite locations and identical core suture purchase length to ensure consistency within and between repairs. Due to a consistent difference in mode of failure between the two groups, it appears that the SSS has the ability to engage and grip the tendon fibrils much more effectively than the 3LP.

During the inflammatory phase of tendon healing, particularly between days 7-14, proteolytic enzymes are at their highest levels, promoting collagen degradation and softening of the lacerated tendon ends. This inflammation and softening of tendon immediately adjacent to the laceration may compromise the tissue strength and the ability of a sutured tenorrhaphy to hold within the tendon when placed under load. Therefore, the suture pattern's physical interaction with the tissue could be an important factor contributing to its mechanical success or failure during this early post-operative period. As suture passes through the tendon stroma, the pattern dictates the ability of the suture to engage or grasp tendon fibrils [18]. Previous studies on the interaction of suture with tissue have shown that the addition of grasping or locking loops to the pattern will increase the patterns ability to resist failure by pull through [46].

Biomechanical testing in this study was performed *in vitro* on normal healthy tendon and demonstrated pull through as a consistent mode of failure for the 3LP pattern This finding is in agreement with previous biomechanical studies of this suture pattern [14,25]. Therefore, we speculate that when applied in an *in vivo* model, employing lacerated tendon, the stroma would be further compromised due to inflammation and remodeling, weakening the tendon's ability to resist pull through. In comparison, the mode of failure of the SSS was due to suture breakage in all tests. This difference underscores the importance of a grasping pattern to grasp tendon fibrils in contrast to a pattern that relies on cross-linking for resistance to pull through. By engaging the tendon fibrils for strength, the pattern may have a higher chance of success in an *in vivo* model.

Testing of the tenorrhaphy constructs in this study utilized high-speed video coupled with analysis software to track distraction of the tendon ends. Other studies have utilized similar methodologies [4,43,47,48] with the benefit of slow speed analysis of construct failure and gap formation. The physical attachment of soft tissues to a testing machine has historically been problematic due to grip slippage and failure [49]. Specimen attachment is an important factor for evaluation of the strength of tissue of interest, and can misrepresent measured biomechanical variables if the tissue is not grasped uniformly by the grip [50]. Our study employed cryofixation to freeze the tendon ends instantly into the custom designed aluminum grips. Testing was completed within 2 minutes of grip application, and the region of the tendon tested for suture strength and grasping remained unfrozen during testing. Cryofixation based grips have been used in biomechanical studies of tendon [50-52] and other soft tissues [49,53]. This attachment method had zero slippage during the testing of the tenorrhaphy.

Gap formation at the repair site is an important factor to control for a successful repair [54]. Gapping can result in poor quality repair tissue [39,55], reducing the ability of the horse to regain athletic function [30]. By reducing gap formation, intrinsic healing can occur, improving the histologic quality of the healed tissue [54]. Experimentally, tendon that has healed without intervention has less mature, disorganized fiber histology [4] and has greater stiffness that that of intact, normal tendon [56]. In fact, strength testing in an ovine model of tendon healing was 56.7% weaker than normal after twelve months of healing [57].

In addition to reduced tissue quality and strength, the risk of adhesion formation is increased with gap formation [13,58]. The 3LP was used in a DDFT intrathecal model and resulted in 50mm gap [13]. Gaps of greater than 3mm in other animal models have been consistent with adhesion formation and a poor result [55,59]. Our testing of the 3LP and SSS tenorrhaphies in equine tendon did not highlight significant difference resistance to gap formation in a pull to failure test. While there was no benefit detected during static 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 [40]. 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.

Tendon perfusion and biomechanical properties following cyclic loading were not examined in this study. The 3LP is superior to a locking loop pattern because it did not greatly inhibit tendon perfusion in an experimental model [60]. Because the SSS is a grasping nature, its effect on perfusion of the lacerated tendon is unknown. However, the grasping bites in the SSS suture pattern are 10mm distant to the transected ends of the tendon which may allow sufficient blood supply to the laceration for healing.

Creating a strong repair and reducing gap formation are very important for successful tenorrhaphy in horses. Surgical techniques to accomplish these goals continue to be improved. The six-strand Savage pattern l repair technique for equine SDFT laceration, , is significantly stronger and more resistant to failure by tendon pull through than the currently accepted repair technique, the three-loop pulley pattern. The SSS pattern is not less resistant to gap formation than the 3LP. Further *in vitro* investigation of other key factors such as resistance to cyclic fatigue and effects on perfusion are needed before clinical application can be recommended.   Additionally, static pull to failure testing does not adequately mimic the forces produced on an *in vivo* repair [39] and may overestimate the tensile strength of the repair [61]. Studies performed using cadaveric human and porcine tendon suggest that the biomechanical properties of the tenorrhaphy change after cyclic loading [61-63]; it will be important to study the SSS repair's resistance to cyclic fatigue [40,62].

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Tables:

Table 1: Ultimate failure load, mode of failure, and stiffness data.

Horse	Failure (N)		Failure Mode		Stiffness (N·mm^{-1})	
	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: Load to produce 3 mm gap.

Horse	Load at 3mm Gap (N)	
	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

Chapter 3
Conclusions

Equine flexor tendon is a dynamic, complex tissue that enables increased efficiency of locomotion. Laceration of flexor tendon poses a significant threat to life and athletic potential of the horse. Multiple challenges are presented to the equine surgeon charged with repair of these tissues. These challenges include sepsis, immediate weight bearing, and prolonged convalescence with external coaptation which by itself can lead to complications.

Previous research in equine tenorrhaphy has shown a benefit to repair if the laceration is greater than 50% of the tendon, as well improvement in ultimate strength and gap resistance by using a three-loop pulley repair. Despite this progress, a variable level of success is observed ranging between 16-51% of horses returning to their pre-injury level of performance. Failure of the repair or less than optimal healing due to excessive gap formation, leads to unacceptable clinical results, highlighting the need for improved methods to optimize outcome.

Morbidity associated with lacerations of digital flexor tendons in humans has prompted investigation into methods of increasing ultimate strength and resistance to gap formation. These qualities are important to enable effective physiotherapy and improve clinical outcome in the form of fine motor skills in these patients. This research has suggested that patterns such as the six-strand Savage suture pattern provide a strong, gap resistant tenorrhaphy.

Adaptation of the six-strand Savage to equine tendon in this study increased the ultimate strength of the repair, without additional gap formation, when compared to the current standard, the three-loop pulley. These results are encouraging, and suggest that further examination of this pattern is warranted. However, the effect of this novel pattern on equine flexor tendon blood flow dynamics remains unknown; therefore, more

information about the effect of this pattern on healing *in vivo* is needed. Additionally, measurement data were collected in a single-cycle-to-failure design, which does not accurately mimic the cyclic tensile forces placed on the tenorrhaphy in a live horse. Further benefits of the six-strand Savage may be found in additional cyclic loading studies, given its high ultimate strength relative to the currently employed tenorrhaphy in horses.