Microangiographic Comparison of the Effects of Three-Loop Pulley and Six-Strand Savage Tenorrhaphy Techniques on the Equine Superficial Digital Flexor Tendon

Kendra D. Freeman

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Jennifer G. Barrett
Nathaniel A. White II
Kenneth E. Sullins

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Abstract

Injuries to the equine distal limb are common and often involve synovial, tendinous and/or ligamentous structures. Historically, lacerations involving the equine digital flexor tendons carried a poor prognosis for return to athletic function due to contamination of the site at presentation, involvement of multiple anatomic structures and the need for immediate weight bearing after surgery. The need for weight bearing after surgery places strain on the tenorrhaphy site that exceeds the strength of the repair itself. Extrapolation of complex, stronger tenorrhaphy patterns from human literature and applying them to equine patients has been challenging.

Human tenorrhaphy techniques initially focused on strong repairs, which are able to match or exceed the strength of tendon itself. Adhesion formation is problematic in human flexor tenorrhaphies, as most injuries occur to tendons surrounded by synovial structures. Human literature now focuses on using repairs that provide initial strength, minimal damage to intrinsic tendon architecture, and allow for early mobilization. This treatment protocol has greatly improved the functional outcome of human tenorrhaphies.

Recent studies have evaluated the strength of complex tenorrhaphy patterns in equine superficial digital flexor tendons, using modifications of the Savage technique. The newly evaluated patterns are stronger than previously tested and commonly used techniques, such as the three-loop pulley (3LP). A review of tendon vasculature across species and healing characteristics of tendons highlights the importance of intrinsic
tendon vasculature in the healing process. Using tenorrhaphy techniques that preserve this vasculature may improve the clinical outcome in these cases. Only one study has previously evaluated the effect of tenorrhaphy patterns on intrinsic tendon vasculature in equine superficial digital flexor tendon.

This study compared perfusion of intrinsic tendon vasculature of equine superficial digital flexor tendon (SDFT) after 3LP and six-strand Savage (SSS) tenorrhaphies. We hypothesized that the SSS technique would significantly decrease vascular perfusion compared to the 3LP technique.

Under general anesthesia, eight pairs of forelimb SDFTs were transected and either SSS or 3LP tenorrhaphy was performed on each forelimb. The horses were heparinized, euthanatized, and forelimbs perfused with barium sulfate solution then fixed with formalin under tension. The tendons were transected every 5mm and microangiographic images were obtained using a Faxitron X-ray cabinet with computed radiography imaging. Microvascular analysis of sections proximal to the tenorrhaphy, throughout the tenorrhaphy and distal to the tenorrhaphy was completed using Image J software and a custom macro.

A significant reduction in the number of perfused vessels was seen in the SSS compared to the 3LP at two locations within the tenorrhaphy ($p=0.004$ and 0.039). The SSS technique took on average $4.7 \pm 0.9$ times longer to place.

The SSS technique causes a reduction in tendon perfusion compared to the 3LP, which may limit its clinical use. Further research is required to elucidate the clinical significance of this difference.
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Attributions

The committee members were involved in the project and contributed to the conceptualization, execution of the research and production of the thesis.

Jennifer G. Barrett – DVM, PhD, Diplomate ACVS, Diplomate ACVSMR (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 tissue engineering and regenerative medicine. Dr. Barrett has earned a PhD in molecular biology and has extensive research experience. She played a vital role in the overall project design and execution as well as the 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 project design and thesis review.

Kenneth. E. Sullins – DVM, MS, Diplomate ACVS (Marion duPont Scott Equine Medical Center, Virginia-Maryland Regional College of Veterinary Medicine) is a committee member. Dr. Sullins has extensive clinical experience in the treatment of equine lameness and emergency case management. He contributed significantly to the review of the thesis.
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Thesis Organization

This thesis is organized into three chapters. The first chapter provides a review of literature pertaining to tendon repair and healing. The second chapter contains a journal publication entitled “Microangiographic comparison of the effects of three-loop pulley and six strand Savage tenorrhaphy techniques on the equine superficial digital flexor tendon” and contains its own introduction, materials and methods, results, discussion and references. The final chapter contains thoughts on future research directions.
Chapter One

Clinical Relevance of Tendon Injury

Traumatic injuries to the equine distal limb are common and often occur due to kicks, wire or overreach injuries. Because of the complexity and lack of extensive soft tissue protection of the equine distal limb anatomy, many support structures can be affected by trauma, including the extensor and flexor tendons, suspensory ligament, distal sesamoidean ligaments, neurovascular structures and well as joints and tendon sheaths. 

Injuries to the tendons and ligaments that support the limb can be challenging to treat and generally carry a poor to guarded prognosis for return to full athletic function. Extensor tendon lacerations carry a better prognosis with 80% of horses returning to some level of riding soundness. 

Flexor tendons lacerations have guarded prognosis with 55-58% of horses returning to riding soundness. Injuries to the tendons of the equine distal limb are often complicated by involvement of synovial compartments, wound contamination, and the involvement of multiple structures. A study by Jordana et al found the prognosis for distal limb lacerations was related to the number of structures involved.

Clinical presentation of these injuries varies with some horses presenting with small, seemingly insignificant skin wounds to large palmar metacarpal lacerations with transected tendon fibers visible through the wound. Palpation and ultrasonographic examination of the area can assist in making the diagnosis of a flexor tendon laceration, especially in the case of partial transection. Horses with complete transection of the superficial digital flexor tendon will often present in hyperextension of the metacarpo/metatarsophalangeal joints. Disruption of the superficial and deep digital flexor tendons will cause hyperextension of the metacarpo/metarsophalangeal joint as
well as elevation of the toe during weight bearing.\(^\text{5,6}\) Often, close examination of the site under general anesthesia is required to fully evaluate the extent of the injuries and determine the number of structures involved.

*Tendon Structure and Organization*

The structural and material properties of a tendon are determined by the three dimensional structure and organization of the fibrils. Tenocytes and non-collagenous proteins aid in fibril organization.\(^\text{6,7}\) One of the most studied non-collagenous proteins in tendon is cartilage oligomeric matrix protein (COMP). This molecule is most active in young, growing animals, appears to be involved in the organization of collagen fibrils during growth\(^\text{6}\), and has been shown to accelerate collagen fibrillogenesis \textit{in vitro}.\(^\text{8}\) Increased concentration of COMP has been identified in areas of equine tendon under tension, peaking during the first two years of life. The more COMP that is synthesized during growth phase, the stronger the resulting tendon.\(^\text{8}\)

Tendon extracellular matrix is a gel-like substance with varying composition along the length of a tendon and serves to provide the gliding functions of tendons\(^\text{9,10}\). Large proteoglycans such as aggrecan and versican are present in highest concentrations in areas of compression along the tendon, (i.e. deep digital flexor tendon over the proximal sesamoid bones). These proteoglycans have a large water holding capacity due to their high numbers of highly sulfated glycosaminoglycan side chains, allowing them the resist compression.\(^\text{8}\) Smaller proteoglycans such as decorin, fibromodulin, and lumican predominate in areas of tension\(^\text{7,8}\) and are involved in the regulation of collagen fibril diameter.\(^\text{11}\)
Tendons are composed of highly organized collagen fibers, collected into bundles, and surrounded by a gel-like extracellular matrix. Tendon has low cellularity and vascularity with abundant extracellular matrix. The extracellular matrix is composed of collagens, proteoglycans, glycoproteins, and glycosaminoglycans. The predominant fibrillar collagen in tendon is type I collagen. The smallest unit of in the tendon structure is the tropocollagen, a triple helical structure, followed by sequentially larger microfibrils, subfibrils and fibrils (Fig 1). Fibrils together with fibroblasts form tendon fascicles. Fascicles measure 0.8-1.2mm in diameter and form a characteristic wave form or crimp when viewed microscopically. This crimp pattern contributes to tendon elasticity allowing the tendon to elongate during early loading. The larger diameter fascicles provide strength and smaller diameter fibers contributing to elasticity. Fascicles and associated connective tissue form the functional tendon unit. The tendon fibers are often described as longitudinal structures. While this is mostly true, in some tendon regions the fibers are arranged in a spiral or helical pattern. This allows for more even distribution of load during increased tension while changing direction around a joint (i.e. sesamoid bones at the fetlock joint). This arrangement decreases tendon distortion during range of motion, lessens friction between tendon fibers and causes less interference with intrinsic blood vessels.
The functional tendon unit is surrounded by the epitenon. This structure is connected to the paratenon, a connective tissue layer present in non-synovial regions. The paratenon connects the epitenon to the connective tissue surrounding the tendon and decreases the frictional forces placed on the tendon by surrounding structures as well as the provides vascular support and cellular elements necessary for repair of the damaged tendon. The epitenon is continuous with the connective tissue that surrounds fascicles called the endotenon. The endotenon is important as blood vessels and nerves course within the endotenon to reach the fascicles throughout the tendon. Type I collagen predominates within the tendon while type III collagen predominates in the endotenon and epitenon.
**Tendon Anatomy**

Movement of the equine distal limb is made possible, in part, by groups of flexor and extensor muscles. The forelimb extensor group contains the *m. extensor carpi radialis*, *m. extensor digitorum communis*, *m. extensor digitorum lateralis* and *m. ulnaris lateralis*, all innervated by the radial nerve, while the hind limb extensor group is composed of *m. tibialis cranialis*, *m. extensor digitorum longus*, *m. peroneus tertius* and *m. extensor digitorum lateralis* innervated by the fibular nerve.\(^{16,17}\) The forelimb flexor group is composed of the *m. flexor carpi radialis*, *m. flexor carpi ulnaris*, *m. flexor digitorum superficialis*, *m. flexor digitorum profundus* and *interossei* innervated by the median and ulnar nerves. The hindlimb caudal muscle group consists of the *gastrocnemius*, *flexor digitorum superficialis*, *flexor digitorum profundus*, *popliteus*, and *interosseous* and muscles innervated by the tibial nerve.\(^{16,17}\)

The most clinically relevant musculotendinous units of the equine distal forelimb are the *m. flexor digitorum superficialis* and *m. flexor digitorum profundus*. The *m. flexor digitorum superficialis* originates from the medial epicondyle of the humerus as well as the caudal radius. The musculotendinous unit travels distad on the caudal aspect of the limb, joining with its accessory ligament (proximal check ligament) at the level of the distal radius. The superficial digital flexor tendon continues through the carpal canal, coursing distad just deep to the skin and superficial to the deep digital flexor tendon along the palmar metacarpal region. The tendon divides into two branches at the level of the proximal phalanx and coursing on either side of the deep digital flexor tendon to insert on the distal aspect of the proximal phalanx and the proximal aspect of the middle phalanx. The *m. flexor digitorum profundus* originates on the humerus, olecranon and
radius. It courses in a similar manner along the caudal aspect of the antebrachium and through the carpal canal. It joins its accessory ligament (distal check ligament) in the proximal metacarpal region, and continues distad along the palmer metacarpal region deep to the superficial digital flexor tendon and superficial to the interosseous ligament. The tendon ultimately inserts on the distal phalanx.  

The forelimb flexor group travels through two synovial structures: the common carpal sheath of the flexor tendons and the digital flexor tendon sheath. The purposes of these synovial structures are to protect the flexor tendons and provide lubrication in regions of joint movement. The proximal extent of the carpal sheath is located 8-10 cm proximal to the carpus, and extends distad to the level of the mid-metacarpus. The flexor tendons are located within a component of the common sheath called the carpal canal. The borders of the carpal canal include the carpal flexor retinaculum, accessory carpal bone and the carpal ligament. Within this structure the superficial digital flexor tendon has a close association with the medial palmar vein and nerve.  

The digital synovial sheath begins in the distal metacarpal region, above the metacarpophalangeal joint and extends distad to the level of the mid-second phalanx and navicular bone. The T ligament separates the digital synovial sheath from the podotrochlear (navicular) bursa. Within the digital synovial sheath, the proximal portion of the deep digital flexor tendon is encircled by a thin sleeve of the superficial digital flexor tendon called the manica flexoria.  

*Techniques to Determine Normal Vasculature*  

Identification of tissue vasculature can be performed using several methods. The method used depends on the invasiveness of the procedure, ease of use and the use of
patients vs. postmortem samples. In living tissue the use of ultrasonography, computed tomography, and magnetic resonance imaging are commonly used. Doppler ultrasonography analyzes frequency shifts of echoes scattered by red blood cells to measure velocity of blood flow.\textsuperscript{19,20} Color flow Doppler has been used to identify neovascularization in chronic tendinopathy patients.\textsuperscript{21} Power Doppler used the amplitude of signals received from tissue to quantify the number of moving red blood cells in a region of interest.\textsuperscript{20} Power Doppler ultrasonography can detect vessels as small as 0.3mm in diameter and is superior than color flow Doppler in low flow regions.\textsuperscript{22,20} Power Doppler has been shown to be more sensitive at detecting microvasculature in human Achilles tendon compared to color Doppler. This is because power Doppler is not as dependent on alignment of the probe with flow as color Doppler.\textsuperscript{23}

Three dimensional microvascular imaging can be accomplished with three-dimensional computed tomographic angiography. This has been used to determine three dimensional anatomy and structure of vessels for neurovascular and abdominal vascular surgery as well as reconstructive surgery.\textsuperscript{24-31} This technique uses a narrow x-ray beam and multiple detectors that rotate 360 degrees to generate cross-sectional data for a region of interest. Computer reconstruction of the region is used to create the three dimensional image.\textsuperscript{31} Magnetic resonance imaging techniques have been used to evaluate cardiac perfusion in myocardial infarction patients.\textsuperscript{32} A more sensitive method of this type of imaging is dynamic contrast enhanced magnetic resonance imaging. This technique uses sequential images obtained before, during and after injection of contrast agents. With this technique differences in blood volume and vascular permeability can be identified. This
has proved useful in the detection and diagnosis of neoplastic conditions in humans. In addition, it can be used to detect response to anti-angiogenic oncology treatments.33-36

In postmortem tissues, the use of radiopaque substances, dyes, silicone mixtures and radioisotopes have been used to determine the vascular anatomy of tissues.37-42 Many anatomical studies of equine tendon vasculature have been performed using barium perfusion studies.37,38,43 Different barium products and solutions have been used, with smaller particle sizes providing better vascular filling than larger particle sizes.41 Radiographic angiography can provide detailed images of microvasculature; however, limitations include the inability to differentiate between vessels in different tissue planes, locations of vessel anastomoses, and differentiation of vessels traversing tissue planes.31

**Tendon Vasculature**

Tendons receive their blood supply from several sources including the musculotendinous or osteotendinous junctions, vessels derived from the tendon sheath and the paratenon.42,44-46 Using barium perfusion studies Kraus-Hansen et al described the vascular supply of the equine superficial digital flexor tendon (SDFT) as a network of anastomosing vessels within the tendon body with large parallel vessels coursing longitudinally at the medial and lateral aspects of the tendon.37,47 Additionally, a branch of the median artery was consistently present within the accessory ligament of the SDFT.37 Work by Stromberg identified a decreased number of intrinsic vessels in equine flexor tendons in middle and distal portions of tendons compared to proximal regions.41

In regions of flexor tendons outside of a synovial structure, the paratenon is involved in vascular support of the tendon. The vessels in the paratenon have a transverse orientation. These vessels traverse through the epitenon. At this level the vessels branch
into arcades and enter the tendon. Each arcade has limited anastomotic connections with other adjacent arcades. Even with the anastomotic connections the arcades are only able to supply vascular supply to a limited, regional area.\textsuperscript{42} In human flexor tendons the segmental arcades supply areas of no more than one centimeter in length.\textsuperscript{42}

Within synovial structures, flexor tendons receive their blood supply from mesotendinous attachments to the sheath. Within this common carpal canal the flexor tendons receive their blood supply from the common mesotendon that exits from the caudomedial aspect of the tendons, attaching to the caudal aspect of the sheath. Additionally the superficial digital flexor tendon receives vascular support from its accessory ligament and the medial and lateral vessels entering at the distal reflection of the sheath. The deep digital flexor tendon receives vascular support from its radial head.\textsuperscript{18,41} Mesotendinous attachments in the digital flexor sheath are located at the palmar aspect of the superficial digital flexor tendon and the proximolateral and proximomedial margins of the deep digital flexor tendon.\textsuperscript{18} Synovial sheaths have an increased number of transverse vessels at locations where tendons traverse over changes in limb angles at joints (i.e. sesamoid bones). Intrinsic vasculature is decreased at these locations and the sheaths and mesotendinous attachments at these locations provide additional vasculature.\textsuperscript{42}

\textit{Tendon Healing}

Healing of an injured tendon can be divided into three general stages: Inflammatory, Fibroblastic and Remodeling. During the exudative stage inflammatory mediators such as leukocytes, macrophages and erythrocytes move from the vasculature to the site of injury. This phase lasts 48-72 hours and during this time, the tenorrhaphy
provides all strength to the repair, as the clot at the site of injury provides little strength. During this stage the migrating cells work to remove necrotic tissue, initiate angiogenesis, promote tenocyte proliferation and recruit additional inflammatory mediators.\textsuperscript{48}

During the fibroblastic stage, tenocytes and fibroblasts proliferate and synthesize new extracellular matrix and fibroblasts fill the damaged area, leading to an increase in tendon size.\textsuperscript{49,50} The fibroblasts produce pro-collagen molecules. These alpha-helical collagen molecules are cleaved by collagenases and three of the helices combine to form the triple helical collagen fibril.\textsuperscript{6} These triple helical collagen fibrils form a three-dimensional collagen structure. Type III collagen production predominates at this stage.\textsuperscript{7} The fibroblasts identified in scar tissue of equine superficial digital flexor tendons have different morphology than typical fibroblasts. They have a larger and more rounded nucleus with prominent basophilic cytoplasm, and are larger than tenocytes. It has been postulated that these cells are myofibroblasts. Smooth muscle cells from local blood vessels are recruited to the site of injury and supply these cells to the area.\textsuperscript{50,51} Intrinsic tenocytes and regional myofibroblasts are important at this phase of healing.

The final stage of healing is the remodeling stage, which starts about six weeks after injury. The remodeling phase is important as it determines the final functional properties of the healed tendon. During this stage small, immature collagen fibers coalesce to form bundles of predominately type III collagen fibers, which realign along the long axis of the tendon and provide increased strength to the site.\textsuperscript{7,52} During this process it is important to have the majority of the healing at the damaged tendon ends, with less cell proliferation adjacent to the tendon and surrounding tissues to decrease the
formation of adhesions. In human flexor tendon injury management, controlled early motion exercises are used to limit adhesion formation and to apply stress to the scar to help stimulate tissue remodeling.

Two major mechanisms are thought to contribute to the ultimate healing of a tendon. The extrinsic mechanism involves the movement of inflammatory cells from the periphery to the site of injury to initiate the exudative phase of healing. This process appears to promote adhesion formation during healing. The intrinsic mechanism involves migration and proliferation of cells from the endotenon and epitenon. These cells establish an extracellular matrix at the site of injury as well as an internal neovascular network. This process is responsible for the reorganization of collagen fibers during the final phase of healing. It is likely that a balance of both mechanisms is necessary for tendon healing, making it important to minimize further trauma to the tendon, epitenon, and paratenon as well as the surrounding environment during treatment of a tendon laceration.

The metabolic activity of tendons has been identified to be 7.5 times less than skeletal muscle. In addition, intrinsic tendon vasculature is compromised at sites of friction and compression. Because of the decreased metabolic activity and relative hypovascular regions within tendons, they have a natural ability to function in anaerobic environments. This allows tendons to tolerate loads and tension without development of ischemia.

Both the intrinsic and extrinsic tendon blood supplies are important in the healing process. Diminished blood supply has been demonstrated to impair tendon healing. Following injury, equine tendons heal from both intrinsic or extrinsic mechanisms.
Extrinsic healing involves the ingrowth of cells from the paratenon and is especially active in the repair of damaged tendons within a synovial compartment, often leading to the formation of fibrous adhesions. Intrinsic healing occurs via activation of macrophage-like cells from the epitendon and endotendon. Damage to the intrinsic tendon vasculature has been proposed to promote adhesion formation in human tenorrhaphies although the exact mechanism has yet to be elucidated. A balance between intrinsic and extrinsic healing mechanisms is necessary for healing of the damaged tendon with minimal adhesions.

Tenorrhaphy Techniques in Human Literature

Primary repair of damaged flexor tendons is advised when more than 60% of the tendon cross sectional area has been transected. Although primarily repaired flexor tendons have been shown to have a better functional outcome compared to either delayed repair or tendon grafting, there is no consensus on the best tenorrhaphy pattern to use. Strickland et al. stated that the ideal repair should have minimal gapping, minimal interference with the vasculature, secure suture knots, smooth junction of the tendon ends and provide sufficient strength. One of the first tenorrhaphy techniques widely used was the Bunnell. This pattern consists of multiple diagonal passes of the suture across the tendon, creating multiple figure-of-eights in the tendon. Studies have since found that pattern produces severe constriction of the tendon and focal ischemia.

Methods to increase tenorrhaphy strength include increasing the number of suture passes across the tenorrhaphy, increasing suture size and the addition of peripheral sutures. In an effort to increase the strength of the repair, more complex suture patterns consisting of increased number of suture passes across the tenorrhaphy site were
developed including the modified Kessler, Tsuge, and Savage suture patterns. Patterns such as the Savage technique are advantageous due to multiple suture strands crossing the tenorrhaphy site with minimal exposed suture. This leads to a strong repair with satisfactory gliding function.

Placement of a suture peripheral to the tendon has been advocated to have several benefits. Peripheral patterns have the advantages of providing additional strength to the tenorrhaphy and decreasing gliding friction at the site. The combination of core and peripheral repairs are not only stronger than core repairs alone, they are also more resistant to early gap formation. The Lin-locking peripheral suture has been found to be the strongest peripheral suture, increasing the tensile strength of a core repair by 3.7 fold. The disadvantage of this pattern is its technical difficulty. Currently, the placement of both a multi-strand core suture with a continuous peripheral pattern is recommended; however, pre-operative planning is necessary as circumferential access to the tendon is necessary for any continuous peripheral suture pattern.

**Human Postoperative Rehabilitation Techniques**

Adhesion formation following human flexor tendon repair is common and troublesome, especially for repairs of tendons located within synovial cavities. Prolonged immobilization can lead to development of weaker fascicles, decreased proteoglycan content and overall tendon atrophy. Controlled mobilization is currently recommended in the early postoperative phase to limit formation of adhesions as well as strengthen the healed tendon tissue. Three general methods used to achieve early controlled motion include active extension-passive flexion using rubber bands, passive motion provided by a physical therapist and controlled passive motion with the
patient actively flexing the affected digit. These techniques rely on the strength of the tenorrhaphy to prevent gap formation in the early healing phase. The human digital flexor tendons in the hand need to withstand 10-17 N force during mild to moderate resistance to flexion. Commonly used tenorrhaphy techniques for these injuries provide strength of up to 67 N before ultimate failure, easily overcoming the force placed on the flexor tendons during normal movement. Further studies have identified the exact excursion flexor tendons undergo during range of motion of the joints in the digit. For example, passive motion exercises often involve 3-5mm of tendon excursion by flexing the digits by 10 degrees. Although various braces and splints have been designed to stabilize, support and control the tenorrhaphy site, consequences of overzealous motion or poor patient compliance include separation, elongation or rupture of the repair.

Tenorrhaphy Techniques in Veterinary Medicine

Small Animal

Canine tendon and ligament lacerations that are treated with primary repair include stifle collateral ligaments and Achilles tendon injuries. The most commonly reported suture patterns used in repair of these injuries are the locking loop and three-loop pulley patterns. The three-loop pulley has been found to be stronger in single load to failure than both the locking-loop pattern and a double locking-loop pattern. These suture patterns are often modified to re-attach the Achilles tendon to the calcaneus, including addition of a mesh to strengthen the repair. The strength of repair achieved in canine soft tendon and ligament repairs vary, but are less than those achieved in equine repairs. Biomechanical testing has determined
the strength of the three-loop pulley to be between eight and 145 N, depending on the soft tissue tested.\textsuperscript{97-99} When directly compared to the three-loop pulley, the locking loop pattern has been found to be significantly weaker with a single load to failure of 35 N.\textsuperscript{97,98}

\textit{Equine Implant Material}

Carbon fiber sutures were evaluated in equine flexor tendon repair due to the strength of the implant. The carbon fiber material has been reported to be successful in both clinical and experimental cases; however, outcome variables are different between studies and follow up information was as short as 24 weeks in some of the studies.\textsuperscript{100-103} Although the carbon fiber sutures have been used successfully in other species\textsuperscript{103-106} they have been found to cause a progressive, granulomatous foreign body reaction in equine flexor tendons.\textsuperscript{45} This reaction makes repair with this material weaker than repairs with nylon suture by eight weeks after the repair.\textsuperscript{102}

Bioabsorbable tendon plates have also been used in equine flexor tendon repair. The goal of these implants, made of absorbable poly-L-lactic acid, is to provide a scaffold for fibroblast ingrowth, and a stronger repair.\textsuperscript{107,108} The plates have demonstrated significant strength with a mean load to failure of 1507.08 $\pm$ 184.34 N compared to the mean strength of the three-loop pulley technique, 460.86 $\pm$ 60.93N.\textsuperscript{109} These implants are bulky, present substantial foreign material into a potentially infected or contaminated wound and require extensive dissection around the tendon for placement, limiting their clinical use.

Although many different implant materials have been tested, suture, both absorbable and non-absorbable, is the most common material used for the repair of
tendon lacerations. In general, absorbable suture material is recommended as non-absorbable suture material is thought to decrease the strength of the repair, increase the risk of tissue reaction and have increased adhesion formation.\textsuperscript{48} Non-absorbable suture materials such as nylon and polypropylene do have the advantage of maintaining their tensile strength while the tendon heals. It is possible for any suture material to harbor infection if placed in a contaminated environment, and equine tendon lacerations are often contaminated, if not infected, at the time of treatment. This potential to harbor infection with non-absorbable suture is the major advantage offered by using a monofilament, absorbable suture material such as polydioxanone.

In general absorbable suture material is recommended as non-absorbable suture material is thought to decrease the strength of the repair, increase the risk of tissue reaction and have increased adhesion formation.\textsuperscript{48,85} The most commonly reported suture materials reported in equine flexor tendon tenorrhaphy are polygalactin 910, polypropylene, polydioxanone and nylon.\textsuperscript{1,2,4,109-112} Polyglactin 910 is a braided monofilament, absorbable suture that loses 100\% of its tensile strength by day 35. Polypropylene, a synthetic monofilament material that does not appear to lose any significant tensile strength. It is contraindicated for use in infected tissue and has poor knot security, making it undesirable in equine flexor tenorrhaphies. Polydioxanone, an absorbable, synthetic monofilament suture, loses 50\% of its tensile strength by day 42.\textsuperscript{113,114} Nylon is a non-absorbable material available as either a mono- or multifilament. It loses 30\% of its tensile strength after two years.

Increasing the diameter of the suture material has been used as a way the further strengthen the repair. Merely increasing the suture caliber from 4-0 to 3-0 was shown to
increase the strength of the repair 2-3 fold. Taras et al evaluated 5-0 and 2-0 suture material in both the Kessler and double-grasping patterns. The 2-0 suture material was 167% stronger for the Kessler repair and 391% stronger for the double-grasping pattern compared to the 5-0 suture material. The disadvantage of larger suture material is the potential negative effect on the tendon itself. Hatanaka et al showed that tendon healing was negatively affected by suture material of 3-0 or greater.

**Equine Suture Patterns**

In an effort to strengthen equine tenorrhaphies many suture patterns have been attempted, although the three-loop pulley pattern remains the mainstay of equine flexor tendon laceration repair. The pattern is easy to place, moderate in strength, resists gap formation, and has less negative effect on intrinsic tendon vasculature compared to the locking loop pattern. The three-loop pulley pattern involves placement of three suture loops oriented 120 degrees from each other. Numerous equine studies have evaluated this pattern biomechanically with the strength of the pattern at failure ranging from 245 N to 461 N. The strength of this pattern, regardless of the suture material used, does not come close to the load of 3559 N placed on the equine superficial digital flexor tendon during weight bearing without external coaptation.

Recent equine veterinary literature has evaluated several complex tenorrhaphy patterns in equine superficial digital flexor tendons. Everett et al evaluated the six-strand Savage pattern, compared to the three-loop pulley pattern. The six-strand Savage pattern was first reported in for use in human tenorrhaphies. This pattern contains grasping and locking sutures, better engaging the tendon fascicles than the three-loop pulley technique. Using #2 polydioxanone suture the six-strand Savage pattern was
consistently stronger than the three-loop pulley technique. The mean load to failure of the three-loop pulley technique was 193 N compared to 421 N for the six-strand Savage technique. Importantly, the three-loop pulley consistently failed by suture pulling out through the tendon, because this pattern fails to engage tendon fascicles. Alternatively the six-strand Savage technique always failed by breakage of the suture.\textsuperscript{111}

Smith et al evaluated a modification of the Savage technique in 2011. The pattern was modified to include more passes of suture across the tenorrhaphy site, making the pattern a ten-strand technique. This was significantly stronger than the three-loop pulley technique, using both polyglactin 910 and polydioxanone, with ultimate load to failure 978 N and 965 N, respectively.\textsuperscript{110} A Lin-locking epitenon suture pattern in conjunction with the ten-strand Savage pattern was proven to be stronger than the ten-strand Savage pattern alone, achieving strength of 1105 N when placed with #2 polyglactin 910.\textsuperscript{110}

Figure two: Diagram of the three-loop pulley tenorrhaphy (A) and the six-strand Savage pattern. Adapted from Everett et al 2011.

*Equine Nonsurgical Management*
Some horses with equine flexor tendon lacerations can be treated without tenorrhaphy. These cases are often treated with debridement of the damaged tendon ends and surrounding non-viable or contaminated tissue, aggressive antimicrobial therapy and distal limb immobilization in the form of a splint or cast. This form of treatment is reserved for horses with less than 50% of the tendon being injured. Conservative management of these injuries often carries a worse prognosis compared to surgical intervention, with fewer horses returning to their intended level of work and inferior cosmetic outcome. The most catastrophic long-term complication of non-surgical management of flexor tendon lacerations is breakdown of the palmar support apparatus, with excessive hyperextension of the metacarpo/metatarsophalangeal joint(s). This is especially concerning with conservative management of completely transected flexor tendons.

**Equine Distal Limb Immobilization**

Distal limb immobilization is recommended as part of the treatment of equine flexor tendon lacerations, for both surgically and non-surgically treated cases. A fiberglass cast extending from the proximal metacarpal region to the hoof is often placed at the time of initial treatment. Recommendations are to maintain the horse in the cast for at least six weeks following the injury. This requires a prolonged hospital stay for cast management and the potential for several cast changes depending on the individual horse. Horses can then be transitioned to a splint of splint/bandage combination as the injury heals. Potential complications of prolonged distal limb immobilization include the development of cast sores, client cost, and osteopenia.
A custom-made, fetlock support brace has been reported as an alternative to distal limb casts in the management of equine flexor tendon lacerations. The advantage of this coaptation is ease of bandage changes, allowing long-term management of these cases outside of the hospital, potentially decreasing the cost of treatment to the client. In this series of 15 cases, 80% of horses treated with this coaptation were reported to return to some level of soundness. Although this success rate seems promising, the performance level following treatment was minimal, with the majority of the horses being used for pleasure riding and breeding purposes.

Although external coaptation is recommended to ease some of the tension placed on flexor tenorrhaphy sites, the amount of tension relieved is unknown. The force placed on the equine superficial digital flexor tendon is reported to be 3559 N. This coupled with 3634-4560 limb loading events per day for a horse confined to a stall places large strain on the tenorrhaphy. It would be helpful to know the amount of this load that is shared by external coaptation, but this data is lacking.

**Conclusions**

Treatment of traumatic lacerations of equine flexor tendons remains difficult, with 50-55% of horses returning to athletic function. Lacerations involving more than 50% of the width of the tendon are best treated with primary repair and distal limb immobilization. Human literature initially focused on development a strong repair that could adequately oppose the transected tendon ends. With greater understanding of how damaged tendons heal, the focus shifted to development of tenorrhaphy patterns that were not only strong, but also promoted healing of the tendon with minimal adhesion formation. This led to the development of tenorrhaphy patterns utilizing both core and
peripheral sutures followed controlled physical therapy programs starting shortly after repair. \textsuperscript{54,74,84,90,115,125,126,77,82,117,127} Data is lacking on the effect of these techniques on intrinsic tendon vasculature.

Equine tenorrhaphy research has focused on the development of a repair using material and patterns that are strong in an attempt to withstand forces placed on the tendons during normal weight bearing. \textsuperscript{100,109-111} Recent evaluation of complex patterns such as the six- and ten-strand Savage as well as addition of epitenon sutures have shown that these patterns are much stronger than the commonly used three-loop pulley pattern. \textsuperscript{110,111} Both of these studies were performed \textit{ex vivo} and the effects that these patterns may have on tendon healing have yet to be elucidated.
References


Chapter Two

Microangiographic comparison of the effects of three-loop pulley and six-strand Savage tenorrhaphy techniques on the equine superficial digital flexor tendon

Kendra D. Freeman, DVM, Jennifer G. Barrett, PhD, DVM, Diplomate ACVS,
Diplomate ACVSMR, Daniel W. Youngstrom, BS, Nathaniel A. White, MS, DVM,
Diplomate ACVS

Marion duPont Scott Equine Medical Center, Virginia-Maryland Regional College of Veterinary Medicine, Virginia Tech, Leesburg, VA
Abstract

Objective: Equine flexor tendon lacerations can be severe and life threatening. The six-strand Savage (SSS) tenorrhaphy pattern is biomechanically superior to the commonly employed three-loop pulley (3LP); however, its effects on intrinsic tendon vasculature remain unknown. The objective of this study was to compare perfusion of intrinsic vasculature of equine superficial digital flexor tendon (SDFT) after 3LP and SSS tenorrhaphies. We hypothesized that the SSS technique would significantly decrease vascular perfusion compared to the 3LP technique.

Study Design: Ex vivo, randomized, paired design.

Animals: Eight mature horses.

Methods: Under general anesthesia, eight pairs of forelimb SDFTs were transected and either SSS or 3LP tenorrhaphy was performed on each forelimb. The horses were heparinized, euthanatized, and forelimbs perfused with barium sulfate solution then fixed with formalin under tension. The tendons were transected every 5mm and microangiographic images were obtained using a Faxitron X-ray cabinet with computed radiography imaging. Microvascular analysis of sections proximal to the tenorrhaphy, throughout the tenorrhaphy and distal to the tenorrhaphy was completed using Image J software and a custom macro.

Results: A significant reduction in the number of perfused vessels was seen in the SSS compared to the 3LP at two locations within the tenorrhaphy ($p=0.004$ and 0.039). The SSS technique took on average $4.7 \pm 0.9$ times longer to place.
**Conclusions**: The SSS technique causes a reduction in tendon perfusion compared to the 3LP, which may limit its clinical use. Further research is required to elucidate the clinical significance of this difference.
Introduction

Injuries to the equine distal limb are common and often involve the extensor or flexor tendons. These injuries can be challenging to treat and generally carry a guarded to poor prognosis for return to full athletic function. Extensor tendon lacerations carry a better prognosis with 80% of horses returning to some level of riding soundness. Flexor tendons have a more guarded prognosis with 55-58% of horses returning to riding soundness. Injuries to the tendons of the equine distal limb are often complicated by involvement of synovial compartments, wound contamination, and the involvement of multiple structures. The prognosis for return to soundness decreases with an increase in the number of associated structures affected.

Primary repair of tendon lacerations can be challenging; however, superior healing has been shown following tenorrhaphy. The goals of tendon repair are to limit gap formation, minimize damage to the intrinsic tendon vasculature and prevent or reduce the incidence of adhesion formation. For a number of years, the most common and often most recommended repair technique used in equine flexor tenorrhaphies is the 3LP pattern. Compared to the locking loop pattern, the 3LP technique is easy to place, moderate in strength, and reduced perfusion less. The 3LP pattern does not contain locking or grasping sutures to engage the tendon fascicles and consistently fails by suture pull through along the tendon parenchyma. There has been testing and application of more complex patterns. These patterns have an increased number of suture passes crossing the tenorrhaphy site, which is correlated with increased strength of the suture pattern. Biomechanical studies have shown that either a six-strand Savage or ten-strand Savage repair technique in the equine SDFT is stronger than the 3LP. These
studies tested the strength and failure mechanism of the suture patterns but not the effect of these techniques on intrinsic tendon vasculature or healing.

Tendons receive their blood supply from several sources including the musculotendinous junctions and vessels derived from the tendon sheath and the paratenon.\textsuperscript{20, 21} Barium perfusion studies have been used to further characterize the vascular supply of the equine flexor tendons.\textsuperscript{22-24} Kraus- Hansen \textit{et al} described the vascular supply of the equine superficial digital flexor tendon (SDFT) as a network of anastomosing vessels within the tendon body with large parallel vessels present longitudinally at the medial and lateral aspects of the tendon.\textsuperscript{23} Additionally, a branch of the median artery was consistently present within the accessory ligament of the SDFT.\textsuperscript{23} This intratendinous blood supply to the tendon is potentially more important than the paratendinous supply to facilitate healing.\textsuperscript{25} A decrease in vascular filling has been found following tenotomy, with a more drastic decrease following repair with a modified Bunnell-type suture pattern. Tendons that underwent this repair also had increased adhesion formation. The authors proposed that ischemia caused by damage to the intrinsic vasculature may have contributed to adhesion formation.\textsuperscript{26} The compound locking loop and 3LP patterns have both been shown to negatively affect the vasculature in the equine superficial digital flexor tendon.\textsuperscript{12} Though the strength of the repair is important to decrease any gap formation after the tenorrhaphy, this must be balanced with the potential detrimental effect on intrinsic tendon vasculature.

The purpose of this study was to compare the effects of the SSS and 3LP techniques on equine intrinsic tendon vasculature. We hypothesized that the SSS technique will reduce the number of perfused vessels in comparison to the 3LP technique.
Specifically, we hypothesized that the region of the SSS pattern containing locking cruciates will have less perfused vessels than the 3LP. However, because the locking cruciate bites are >5mm distant from the tendon transection, we hypothesized that within 5mm adjacent to the transection, there will be no difference in the number of perfused vessels.

**Materials and Methods**

*Experimental Design*

Eight horses had one forelimb of each pair randomly assigned to 3LP, and the contralateral to SSS. Two surgeons (JGB and KDF) performed tenorrhaphies simultaneously, as determined by random assignment. Surgery was performed on live horses under general anesthesia, horses were then heparinized and euthanatized. Forelimbs were perfused with barium and fixed with formalin for microangiography with a tensioning device to standardize positioning. Microangiography was performed with identical settings on every limb; the deep digital flexor tendon (DDFT) and non-sutured SDFT were used as internal controls for each limb to verify perfusion. Microangiographic images were objectively analyzed using a custom macro in Image J and statistical analysis was performed with JMP 10.

*Sample population*

Eight mature horses with clinically normal tendons were selected for inclusion in the study. The horses were euthanized at the owner’s request for reasons other than lameness or injury associated with the flexor tendons. The study was approved by the Virginia Tech Institutional Animal Care and Use Committee.

*Surgical procedure*
An intravenous catheter was placed, horses were sedated and induction and maintenance of general anesthesia was maintained with ketamine, guaifenesin and xylazine. Horses were positioned in dorsal recumbency with the forelimbs suspended in full extension. The hair over the palmar aspect of the metacarpal region of each forelimb was clipped and prepared for aseptic surgery.

The SDFTs were randomly assigned to one of the treatment groups. Eight tendons were assigned to the 3LP group and SSS group respectively. All tenorrhaphies were performed simultaneously by one of two individuals (JGB and KDF). Random assignment was used to determine the pattern performed by each surgeon. Tenotomies were completed using a palmar approach through a 12cm longitudinal skin incision centered over the SDFT, 15cm proximal to the ergot. Blunt and sharp dissection was used to expose the SDFT. A 5cm incision was made in the paratenon to isolate it from the SDFT using blunt and sharp dissection. At 15 cm distal to the accessory carpal bone, the SDFT was sharply transected and one of the two tenorrhaphy techniques was performed with 2 polydioxanone on a preswaged CP (cutting point) 0.5 x 40mm reverse cutting needle (Ethicon Inc., Somerville, NJ). Both patterns were started 5mm from the transected tendon ends and completed within 2 cm of the tenorrhaphy. For all tenorrhaphies a surgeons knot and four throws were used to secure the suture. Time of tenorrhaphy placement was recorded and commenced once suture placement started and ended after the tightening of the final throw of the knot. At completion of the tenorrhaphy, heparin sodium (200 U/kg, IV) was administered to each horse. Fifteen minutes after administering heparin the horses were euthanized.

_Tensioning Device_
The forelimbs were amputated at the level of the mid-radius. In order to apply load to the tenorrhaphy, similar to Crowson et al., a tensioning device was applied to standardize tension and place the metacarpophalangeal joint in a slightly hyperextended position (Fig 1). This device was not intended to mimic the tension during full weight bearing, since splinting or external coaptation is most common after tenorrhaphy. In brief, holes were drilled in the toe of the hoof and in the proximal radius using a 15.9mm drill bit. A 12.7mm diameter eyebolt with washers was secured into each hole. A ratcheting tie strap (Erickson MFG LTD, Cottrellville, MI) in line with a digital tension gage (American Weigh Scales Inc., Norcross, GA) were placed dorsal to the limb from one eyebolt to the other. The ratcheting tie strap was tightened until the digital tension gage showed 200N of force was being applied between the two eyebolts. Each pair of forelimbs was prepared in precisely the same manner in tandem to avoid confounding variables.
Fig 1: Perfused limb with tensioning device. The eyebolts are secured to the distal radius as well as the hoof. The tension strap and gauge are spanning the eyebolts, on the dorsal aspect of the limb, with the gauge tensioned to 200N.

Perfusion technique

A 4.7mm red rubber catheter (Tyco, Mansfield, MA) was placed into the median artery proximal to the musculotendinous junction of the SDFT, and secured with a purse-string suture. A suspension of 600mL barium sulfate (EZ-EM, Lake Success, New York) and 800mL water was perfused the limb via the red rubber catheter at a constant pressure of 250mmHg using an Arthro-Flo (C.R. Bard, Inc., Warwick, RI). Eighty milliliters of 10% buffered formalin (Fisher Scientific, Baltimore, MD) was added to the final 150mL of the barium suspension and the limbs were fixed at 4°C for 18 hours with 200N of tension. Each SDFT and DDFT was dissected from the limbs. The tendons were
transected proximally at the level of the accessory carpal bone and distally at the level of the metacarpalphalangeal joint. The DDFT, which was neither transected nor sutured, served as an internal control for perfusion of the flexor tendons.

**Microangiographic protocol**

The SDFTs were manually transected with a #10 scalpel blade into 5mm sections along the length of the tendon. The cuts started at the tenorrhaphy site and extended proximad to the level of the accessory carpal bone and distad to the metacarpophalangeal joint. The DDFTs were manually transected into 5mm sections and used to verify perfusion of each limb.

The 5mm sections were transferred to a high detail radiographic cassette for soft tissue radiography. Each SDFT was divided into six regions (Fig 2) in order to determine if the different regions of the SSS pattern have different effects on vessel perfusion. Specifically, the SSS pattern has locking cruciate bites at the proximal and distal extent of the pattern, but adjacent to the transection or laceration, the suture pattern does not grasp the tendon fascicles. The regions spanned from proximal to distal, starting with region A, which was proximal to any suture placement. For the SSS pattern, Region B contained the locking cruciate sutures. Region C contained sutures parallel to the tendon fibrils. Region D contained sutures parallel to the tendon fibrils, but distal to the transection. Region E contained the locking cruciate sutures distal to the transection zone. Region F was tendon distal to any suture placement. For the 3LP pattern Region B and C contained suture proximal to the transection. Regions D and E contained sutures distal to the transection and Region F contained tendon distal to any suture placement (Fig 2). Tenorrhaphy sutures were removed from the sections prior to imaging. A cabinet x-ray
system (Faxitron Series, Hewlett-Packard, Palo Alto, CA) was used at 30 kVp and 5mAs. Tendons from each forelimb were radiographed separately along with the sectioned DDFTs to control for perfusion of the limb. The cassettes were processed using a computed radiography processor (Fujifilm Corporation USA, Valhalla, New York) No contrast or brightness changes were made to the images.

Figure 2: Tenorrhaphy regions for microangiographic analysis from proximal (A) to distal (F). Regions A and F are unsutured regions of the tendon (proximal and distal, respectively). In the six-strand Savage pattern (left) regions B and E contain the cruciate suture regions and regions C and D contain the linear suture patterns. In the three loop pulley pattern (right) regions B, C, D and E contain sutured tendon.

Image Analysis

Digital radiographic images of the SDFT sections were quantitatively interpreted using a custom semi-automated analysis macro in Image J (National Institutes of Health, Bethesda, MD). Briefly, isolated points of radio-opacity representing vascular cross-
sections were demarcated using a thresholding procedure and counted with a standard particle analyzer. Raw vascular count data was obtained and organized by region for comparison.

*Data Analysis*

Vascular perfusion is presented as mean ± standard error of the total vascular count registering as radiopaque per tissue section. Differences between contralateral treatment groups were assessed by implementing a one-way paired Student’s t-test, signified with an asterisk. Within-subject effects comparing tenorrhaphy perfusion (regions B-E) to non-sutured segments of SDFT (regions A and F) were analyzed with a one-way repeated measures multivariate analysis of variance (MANOVA). Times to complete tenorrhaphy were not normally distributed. Non-parametric data were assessed for significant differences using the Wilcoxon signed rank test, The threshold for determining statistical significance was set at $p \leq 0.05$. Calculations were conducted in JMP 10 (SAS Institute Inc., Rockville, MD) and Excel 12 (Microsoft Inc., Redmond, WA).

*Results*

Perfusion of all pairs of limbs was apparent during the experiment, as barium was seen exiting the transected tendon ends. Minimal gap formation (<3mm) occurred after application of the tensioning device, and all metacarpophalangeal joints were in slight hyperextension. Average surgery times varied between techniques – 3LP: median 3.5 minutes (range 2-5), SSS: median 16.0 minutes (range 9-39). The SSS technique took on average 4.7 ± 0.9 times longer than 3LP, and differential surgery times were positively
skewed ($\gamma_1=1.16$) (Fig 4). This difference was statistically significant as determined via the Wilcoxon signed rank test ($p=0.0013$).

Figure 3: A) Vascular count for each tenorrhaphy pattern by region. Significant differences between the patterns in regions B and C for the six-strand Savage compared to the three loop pulley technique. B) Vascular counts of the deep digital flexor tendons used to evaluate adequacy of perfusion. No difference was present between deep digital flexor tendons on the limbs of sutured tendons. C) Diagram of the two tenorrhaphy patterns and their associated regions for the regions compared with figure A.

Figure 4: Box and whisker plot of surgery times (minutes) for the two tenorrhaphy patterns. The three-loop pulley pattern was quicker to place than the six-strand Savage technique. This difference was statistically significant ($p= 0.0013$).
A significant acute reduction in vascular count was identified in the SSS compared to the 3LP at two regions within the tenorrhaphy. In region B, the raw vascular count of SSS was an average of 31% lower than 3LP. This difference was statistically significant ($p=0.0390$, power 0.72). At point C, there was a significant difference in the raw vascular count of SSS, which was an average of 27% lower than 3LP ($p=0.0044$, power 0.86) (Fig 3A). All perfusions were completed successfully and no significant differences in vascular count were observed DDFTs between untreated limbs (Fig 3B).

For within-group comparison of the SSS pattern, regions B ($p=0.003$), C ($p=0.001$), D ($p=0.009$) and E ($p=0.019$) were significantly lower than region A (proximal SDFT outside of tenorrhaphy). Regions B and C were significantly lower than region F (distal SDFT outside of tenorrhaphy) ($p=0.010$ and $p=0.007$, respectively). For within-group comparisons of the 3LP pattern, regions D and E were significantly lower than region F (distal SDFT outside of tenorrhaphy) ($p=0.012$ and $p=0.035$, respectively).

**Discussion**

Primary repair of tendon lacerations has been validated as superior to second intention healing in multiple studies. Jann *et al* \(^7\) identified stronger healing of sutured tendons at five and nine weeks after repair versus non-sutured tendon. Second intention healing of tendons resulted in hyperextension of the fetlock and increased proliferation of soft tissues leading to a weaker musculotendinous unit, and cosmetic blemish.\(^6\) Because primary repair results in superior healing, many studies have focused on maximizing the strength of repair to overcome the high forces placed on equine flexor tendons.
Following repair to human flexor tendon injuries, early controlled movement is advocated\(^{27,28}\) and associated with rapid recovery of tensile strength, improved tendon excursion, decreased adhesion formation and better overall clinical outcome\(^{29-33}\). Multiple studies have determined the normal amount of flexor tendon excursion and the amount of excursion with various splints and range of motion exercises in normal tendons. This allows for very rigid, controlled treatment protocols\(^{29,34}\). Several limitations currently prevent these types of rehabilitation programs in equine patients.

Equine tenorrhaphies require significantly more strength than human tenorrhaphies. Human flexor tendons must withstand 34-50N\(^{35,36}\) while equine tendons must withstand 3559N in the absence of splinting or coaptation\(^{37}\). Equine patients with flexor tendon lacerations are typically placed in partial flexion of the metacarpo/tarsophalangeal joint through splinting or casting to reduce the tension on the healing tendon. The load applied to the SDFT when the metacarpo/tarsophalangeal joint is in partial flexion in a cast is unknown. Even so, the cyclic loading horses experience (3624-4560 limb loading events per day) when standing in a stall and the tension applied from the muscle can cause gap formation\(^{38,39}\).

Tenorrhaphy patterns either contain locking loops, which tighten around tendon bundles, or grasping loops, which pull through the tendon fibrils when tightened. The 3LP pattern does not contain locking nor grasping sutures. Locking loops are proven to increase the ultimate strength and decrease gap formation at the repair site\(^{17,40-43}\). Suture patterns such as the SSS and its modifications have been advocated due to the presence of locking loop suture compared to the 3LP pattern that only contains longitudinally oriented loops. Although stronger, locking loops can have a negative effect on intrinsic
vasculature compared to grasping loops. It is interesting that in our study only one region of decreased perfusion was located in the locking portion of the SSS pattern. The 3LP also had decreased perfusion in regions of suture placement, compared to regions without sutures, and this pattern contains neither locking nor grasping sutures. Decreased perfusion in only two sections may have little clinical significance if healing is facilitated by the strength of the repair pattern. Ischemia has been proposed to promote adhesion formation in tendon repair, although it is possible that the minor decrease in vascular filling identified in this study would have minimal effect on healing and adhesion development in clinical cases of flexor tendon lacerations.

To date in the veterinary literature modifications of the SSS technique have only been reported in ex vivo studies of equine flexor tendons. This is the first report of placement of the SSS pattern in the superficial flexor tendon using a routine surgical approach. The pattern requires circumferential access to the tendon. The ability to place sutures at exact, predetermined and equal locations, as in done in ex vivo biomechanical studies, is limited in the clinical setting. The SSS pattern took significantly longer to place than the 3LP. The surgery time in a clinical setting would be prolonged further by the need to clean and debride the affected tissue prior to suture placement. In human literature, the SSS technique has had limited use due to its difficulty in placement. Although complex patterns such as the Savage techniques are mechanically superior, their clinical utility may be limited.

Limitations of this study include the ex vivo experimental design, absence of control SDFT for baseline perfusion, and the possibility that transection alone would cause significant reduction of perfusion. Problems with ex vivo experimental design of
tendon repair studies include incomplete understanding of the role of reduced perfusion on tendon healing. Our goal was to investigate one aspect of SSS biological effects prior to conducting a live animal study. Since we were primarily interested in comparison of the commonly used 3LP to the SSS, and since a pilot control horse (data not shown) had excellent perfusion in a control SDFT and DDFT, we opted to use the DDFT and regions of SDFT outside of suture pattern placement as internal controls for tendon perfusion. Other studies looking at the effect of transection on intrinsic vascular perfusion has shown either normal perfusion or a minimal region of reduced perfusion at transection site. The SSS technique is technically challenging and causes a higher reduction in tendon perfusion than the 3LP technique. Although the negative effect on the intrinsic vasculature was more pronounced with the SSS pattern compared to the 3LP, the clinical significance is unknown. The tradeoff between strength of repair and vascular perfusion is one that needs to be carefully considered. Further research is needed to elucidate the effects of these differences on equine tendon healing in vivo.
References


Chapter Three

Equine flexor tendon lacerations remain challenging to treat successfully. The need for immediate weight bearing following surgery, even with the support of external coaptation, puts stress on the newly placed tenorrhaphy. Although complex patterns such as the six- and ten-strand Savage patterns are much stronger than the three-loop pulley pattern, they are not nearly strong enough to overcome the forces placed on the superficial digital flexor tendon during weight bearing in the unsupported limb. These complex patterns, especially those involving the placement of a peripheral suture pattern require circumferential access to the tendon.

Adhesion formation is common in human flexor tendon repair and is often detrimental to the overall outcome of a case. The majority of human flexor tendon lacerations occur in regions of tendons surrounded by synovial structures. These regions are prone to adhesion formation in the healing process. In early human tenorrhaphy repair these locations were considered “no man’s land” and repair was avoided. The development of early mobilization protocols has limited the formation of adhesions in these regions. Because of the need for early mobilization to limit adhesion formation, many human studies have focused on the strength of the repair. Several patterns are strong enough to overcome the strain of early mobilization. Although the Savage pattern and its modifications are biomechanically superior, they are not the tenorrhaphy patterns used. Surgeons use a combination of core and peripheral sutures to limit gap formation and increase initial strength, allowing for early mobilization to decrease adhesion formation.
Preservation of the vascular supply to lacerated tendons is commonly cited as one of the main goals of treatment of these injuries. It has been proposed that damage to this vasculature can contribute to adhesion formation, although the mechanism of this phenomenon is not known. Adhesion formation is more of a concern in treatment of human tendon lacerations compared to equine lacerations. In humans the goal is to achieve a healed tendon that functions mechanically similar to an undamaged tendon. In equine lacerations the goals are to first save the life of the animal and secondly, obtain a healed tendon that can tolerate at least partial return to work.

Research scenarios used to test biomechanical strength of a repair pattern are often much different than what is seen in clinical settings. The clinical case rarely presents with a completely transected superficial digital flexor tendon, in the mid metacarpal or metatarsal region. Clinical cases often involve multiple structures and tendon ends usually require debridement to remove necrotic, contaminated or damaged tissue. It is likely that cases of equine flexor tendon laceration would best benefit from a combination of treatments including debridement, tenorrhaphy and distal limb immobilization, followed by transition to a fetlock support brace or shoe. Even with this combination of therapy, it is important to optimize each step of the treatment to ensure the best cosmetic and functional case outcome.