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Shear lag sutures: Improved suture repair through the use of adhesives

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ABSTRACT

Suture materials and surgical knot tying techniques have improved dramatically since their first use over five millennia ago. However, the approach remains limited by the ability of the suture to transfer load to tissue at suture anchor points. Here, we predict that adhesive-coated sutures can improve mechanical load transfer beyond the range of performance of existing suture methods, thereby strengthening repairs and decreasing the risk of failure. The mechanical properties of suitable adhesives were identified using a shear lag model. Examination of the design space for an optimal adhesive demonstrated requirements for strong adhesion and low stiffness to maximize the strength of the adhesive-coated suture repair construct. To experimentally assess the model, we evaluated single strands of sutures coated with highly flexible cyanoacrylates (Loctite 4903 and 4902), cyanoacrylate (Loctite QuickTite Instant Adhesive Gel), rubber cement, rubber/gasket adhesive (1300 Scotch-Weld Neoprene High Performance Rubber & Gasket Adhesive), an albumin-glutaraldehyde adhesive (BioGlue), or poly(dopamine). As a clinically relevant proof-of-concept, cyanoacrylate-coated sutures were then used to perform a clinically relevant flexor digitorum tendon repair in cadaver tissue. The repair performed with adhesive-coated suture had significantly higher strength compared to the standard repair without adhesive. Notably, cyanoacrylate provides strong adhesion with high stiffness and brittle behavior, and is therefore not an ideal adhesive for enhancing suture repair. Nevertheless, the improvement in repair properties in a clinically relevant setting, even using a non-ideal adhesive, demonstrates the potential for the proposed approach to improve outcomes for treatments requiring suture fixation. Further study is necessary to develop a strongly adherent, compliant adhesive within the optimal design space described by the model.

1. Introduction

Sutures are an age-old technology: they have been used for wound closure for over 5 millennia, dating back to sutures used in ancient Egypt, as described in the Edwin Smith Papyrus from 3000 to 1600 BC [1–3]. While many improvements in suture materials and intricate knot tying techniques have been introduced over the years, the core method of directly sewing tissues together remains a crude mechanical solution. Sutures typically work in pure tension along most of their length. Tension is transferred to the tissue only at anchor points (Fig. 1). High stress concentrations at these anchor points can lead to sutures breaking or cutting through the surrounding tissue. This phenomenon limits the maximum force that can be transferred across the repair site. While current suturing techniques are sufficient to maintain the integrity of many surgical repairs, musculoskeletal tissue reconstruction (e.g., tendon and ligament repair) typically demands strong biomechanical resilience to accommodate activities of daily living without risking rupture. For example, repair-site elongation and rupture rates of up to 48% have been described after flexor tendon repair, even with modern suturing and rehabilitation protocols [4–7]. Rotator cuff repairs, which require reattachment of materials with disparate mechanical properties (tendon and bone), have recently reported failure rates as high as 94% [8–10]. Improved suturing schemes would allow for the transfer of greater loads across the repair site, reducing rupture and gap formation between

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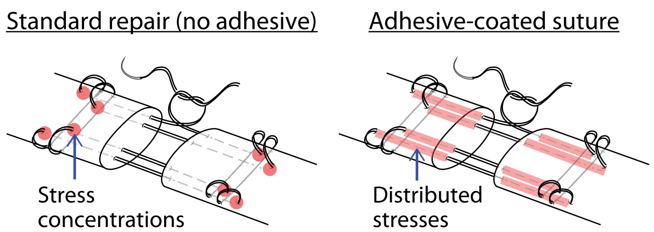

Fig. 1. An 8-stranded Winters–Gelberman suture repair technique is shown for human flexor digitorum profundus tendon repair [11]. Red shading indicates location of load transfer. Current suturing techniques generate stress concentrations at anchor points where the suture bends within tissue. Adhesive-coated sutures could distribute that load transfer along the entire length of the suture, reducing peak stresses and improving overall repair construct mechanics.

the repaired tissues and improving healing outcomes, not only by strengthening repairs but also by enabling more aggressive rehabilitation protocols. By holding the tissues together for longer time intervals, mechanical solutions that prevent gap formation and development could provide more time for the biological healing response to generate a strong, organized tissue instead of disorganized scar [5,11,12].

Here, a new approach is proposed to augment standard suturing technology. Conventional sutures have a relatively large surface area passing through the tendon that is currently not utilized for load transfer. We envision a modified suture with an adsorbed or covalently bound adhesive that tightly binds collagen along the suture's length, thereby reducing stress concentrations and better distributing load (Fig. 1). We hypothesized that adhesives along the length of the suture would transfer load more effectively than conventional suture without adhesive. This improvement in load transfer is expected to result in an improvement in overall repair construct mechanical properties. Note that achieving the full strength of an uninjured tendon is unnecessary, as tendons are over-designed and are typically able to accommodate many times more load than is applied physiologically [13–15]. We aim to generate functional repairs that are sufficient to accommodate *in vivo* loads and enhanced rehabilitation protocols. We focus here on single stranded sutures or pseudo-monofilament sutures, including multiple strands within an outer casing, because these are used surgically for flexor tendon repair [11].

In order to predict the ability of adhesive-coated sutures to improve load transfer, we employed a shear lag model [16–19] of suture within a cylindrical tissue (e.g., a tendon). Using this model, we identified desirable adhesive mechanical properties to improve load transfer across a repair site. We then biomechanically tested sutures coated with adhesives to validate the model and experimentally assess the capacity to improve load transfer.

2. Materials and methods

2.1. Terminology

Throughout this paper, "suture" refers to the core strand of suture, "adhesive" refers to the adhesive layer, "assembly" and "adhesive-coated suture" refer to the combination of suture with adhesive surrounding it, and "repair" refers to the complete tissue repair, including several strands of adhesive-coated suture and a region of tissue in which these are embedded. Abbreviations and variables are described in Table 1.

2.2. Ex vivo surgical repair model

To experimentally assess the ability of adhesives to improve load transfer, a number of adhesive coatings were added to single pseudo-monofilament polycaprolactam 4–0 suture strands (Supramid, S. Jackson, Inc., Alexandria, VA) and inserted into tendon tissue prior to performing pullout tests. Single strands without knots were chosen to isolate the effects of the adhesive and mimic the mathematical model as closely as possible. The following adhesives were examined: highly flexible cyanoacrylates (Loctite 4903 and 4902, based on ethyl and octyl cyanoacrylate [20,21]; Henkel Corporation, Düsseldorf, Germany), cyanoacrylate (Loctite QuickTite Instant Adhesive Gel, based on ethyl cyanoacrylate [22], Henkel Corporation, Düsseldorf, Germany), rubber cement (Elmer's Rubber Cement; Elmer's Products, Inc., Columbus, OH), rubber/gasket adhesive (1300 Scotch-Weld Neoprene High Performance Rubber & Gasket Adhesive; 3 M, St. Paul, MN), BioGlue (CryoLife Inc., Kennesaw, GA), and polydopamine [23,24] (Sigma Aldrich, St. Louis, MO). Henkel does not release the exact chemical composition of their products. Of these adhesives, only BioGlue is FDA approved for use inside the body. These commercially available adhesives were chosen solely to assess the concept proposed here, not to promote the use of any particular adhesive clinically. Loctite 4903 and 4902 have shear moduli of 538 MPa and 399 MPa, respectively [25]. BioGlue, rubber cement, and rubber/gasket adhesives [26] have shear moduli on the order of 0.5–5 MPa [27–29]. Suture was passed through cadaveric canine hindpaw flexor digitorum profundus tendons using a French eye needle. All tendons tested in this study were from hindpaws of healthy female adult mongrel dogs 20–30 kg in weight (Covance Research, Princeton, NJ), taken postmortem from an unrelated project. Canine intrasynovial flexor tendons have been used extensively by our group and others since the early 1960s as a reliable model of human tendon repair; we expect the results from this model to be comparable to those that would be obtained from human flexor tendon reconstructions [5,30–36]. Tendons had elliptical cross sections with major and minor radii approximately 3 mm and 1 mm,

Table 1
Abbreviations and variables used throughout the manuscript.

PBS	Phosphate buffered saline	x	Position along suture
$\tau(x)$	Shear stress in the adhesive layer	τ_{ave}	Average shear stress
τ_{fail}	Failure shear stress of adhesive-coated suture	$\bar{\sigma}_s(x)$	Normal stress in suture normalized by normal stress at $x = 0$
E_s	Suture elastic modulus	E_s^*	Suture elastic modulus normalized by tendon elastic modulus
E_t	Tendon elastic modulus	G_a	Adhesive shear modulus
G_a^*	Adhesive shear modulus normalized by tendon elastic modulus		
L	Suture purchase length	$L_{intersect}$	Suture length where asymptotic limits for load transfer intersect
P_s	Normal force in suture at the interface, $x = 0$	P_k	Resultant normal force in suture at the anchor point
r_s	Suture radius	r_t^*	Tendon radius normalized by suture radius
r_t	Tendon radius	ρ_t^*	Effective radius of tendon, normalized by suture radius
t_a	Adhesive thickness	t_a^*	Adhesive thickness normalized by suture radius
β_s	Characteristic (inverse) length scale related to geometry and material properties	χ	Variable related to geometry and material properties