Mechanical Strength of the Side-to-Side Versus Pulvertaft Weave Tendon Repair

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Purpose The side-to-side (SS) tendon suture technique was designed to function as a repair that permits immediate postoperative activation and mobilization of a transferred muscle. This study was designed to test the strength and stiffness of the SS technique against a variation of the Pulvertaft (PT) repair technique.

Methods Flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP) tendons were harvested from 4 fresh cadavers and used as a model system. Seven SS and 6 PT repairs were performed, using the FDS as the donor and the FDP as the recipient tendon. For SS repairs, the FDS was woven through one incision in the FDP and was joined with 4 cross-stitch running sutures down both sides and one double-loop suture at each tendon free end. For PT repairs, the FDS was woven through 3 incisions in the FDP and joined with a double-loop suture at both ends of the overlap and 4 evenly spaced mattress sutures between the ends. Tendon repairs were placed in a tensile testing machine, preconditioned, and tested to failure.

Results There were no statistically significant differences in cross-sectional area ($p = .99$) or initial length ($p = .93$) between SS and PT repairs. Therefore, all comparisons between methods were made using measures of loads and deformations, rather than stresses and strains. All failures occurred in the repair region, rather than at the clamps. However, failure mechanisms were different between the 2 techniques—PT repairs failed by the suture knots either slipping or pulling through the tendon material, followed by the FDS tendon pulling through the FDP tendon; SS repairs failed by shearing of fibers within the FDS. Load at first failure, ultimate load, and repair stiffness were all significantly different between SS and PT techniques; in all cases, the mean value for SS was higher than for PT.

Conclusions The SS repair using a cross-stitch suture technique was significantly stronger and stiffer than the PT repair using a mattress suture technique. This suggests that using SS repairs could enable patients to load the repair soon after surgery. Ultimately, this should reduce the risk of developing adhesions and result in improved functional outcome and fewer complications in the acute postoperative period. Future work will address the specific mechanisms (eg, suture-throw technique and tendon-weave technique) that underlie the improved strength and stiffness of the SS repair. *(J Hand Surg 2010;35A:540–545. © 2010 Published by Elsevier Inc. on behalf of the American Society for Surgery of the Hand.)*

Key words Early mobilization, flexor tendon, muscle, tendon transfer, tetraplegia.

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THE LONG-TERM GOAL of tendon transfer surgery is restoration of lost function. Previous studies have established that early controlled activity and motion reduce the incidence of adhesion formation, improve range of motion, and reduce postoperative recovery time.[1–3] Further, early activation and loading of the muscle-tendon unit substantially improves tensile strength,[4] vascularity and cellularity[5] of tendon end-to-end repair sites in model systems. However, although the benefits of early motion following tendon repair are supported by basic scientific and clinical studies, many authors have traditionally advocated a period of immobilization following tendon transfer surgery[6–10] to ensure that the repair is strong enough to withstand forces and motion without being compromised. More recent reports have advocated early, active mobilization of transferred muscles.[11–12] Thus, prerequisite for early return to activity is a strong and stiff repair that enables efficient load transfer through the repair, across the joints of interest, and into the bony insertion, with a minimal risk of repair site failure. The side-to-side (SS) repair technique was developed to achieve these goals, and it motivated this study comparing the mechanical properties of the SS with a variation of the Pulvertaft (PT)[13] repair technique in a model system in which tendon size, suture distance, and overlap area were standardized. The PT suture technique was not well defined in the original publication and, consequently, has been varied and applied in different manners; therefore, a specific variation will be tested here. The 2 techniques, as tested in the current study, differ in the following respects: (1) the SS consists of a single weave of the donor tendon through the recipient, whereas the PT consists of multiple weaves of the donor tendon through the recipient; and (2) the SS repair is stabilized using a cross-stitch suture method, compared to mattress sutures in the PT repair. Our comparisons assessed the mechanical properties of the repair techniques, thus simulating the *time zero*, or immediate postoperative state, of the repairs.

MATERIALS AND METHODS

Flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) tendons were harvested from the index through little fingers of single arms of 4 fresh human cadavers (below-elbow amputation specimens). Of the 32 total tendons, 4 were used in pilot testing, and data from 2 others were lost in a computer malfunction (leaving 26 tendons for experimental testing; 2 tendons were sutured together for each mechanical test, thereby enabling 13 test specimens). The mean (± standard deviation) age at death was 85.0 ± 11.9 years. Tendons were soaked in phosphate-buffered saline and frozen for approximately one week immediately following harvest. At the time of testing, tendons were thawed, and repairs were performed, with the FDS tendon serving as the donor and the FDP tendon as the recipient. Seven SS repairs and 6 PT repairs were performed by an experienced hand surgeon (Table 1 shows a comparison of the 2 repair techniques). Green braided 3-0 polyester suture (Ethibond; Ethicon, Inc, Somerville, NJ) was used for all repairs. For the PT repair, the FDS was woven through 3 incisions (2 horizontal and one vertical) in the FDP and was stabilized with a double-loop suture at both ends of the overlap, with 4 evenly spaced mattress sutures between the ends (Fig. 1). Mattress sutures were applied with 2 connection points between the tendons—one at the top of the loop and a second where the stitch was completed. This provided the PT repair with a total of 10 suture points connecting the tendons. For the SS repair, the FDS was woven through one incision in the FDP and was stabilized with 4 cross-stitch running sutures down both sides (8 total cross-stitches) and one double-loop suture at each tendon free end (Fig. 1). This provided the SS repair with a total of 10 suture points connecting the tendons. Each connection point referred to for the SS and PT repairs indicates a strand of suture piercing through and directly interacting with both the donor and recipient tendons, thereby connecting the 2 tendons together. The length of the overlap region was standardized between the 2 techniques and equated to 29.4 ± 1.8 mm for SS and 29.7 ± 1.4 mm for PT ($p = .99$). Clinically, a minimum overlap region of 50 mm is recommended for the SS repair;[11] the smaller overlap length was used here due to limitations imposed by

TABLE 1. Comparison of SS and PT Repair Techniques

Variable	SS	PT
Number of weaves	1	3
Amount of overlap (cm)	3	3
Number of connection points*	10	10
Type of stitch	Cross-stitch, double-loop	Mattress, double-loop
Amount of suture material†	More	Less

*Number of connection points indicates the number of times the suture makes a physical connection between the 2 tendons.
†The amount of suture material was not quantified; therefore, a specific value cannot be attributed.

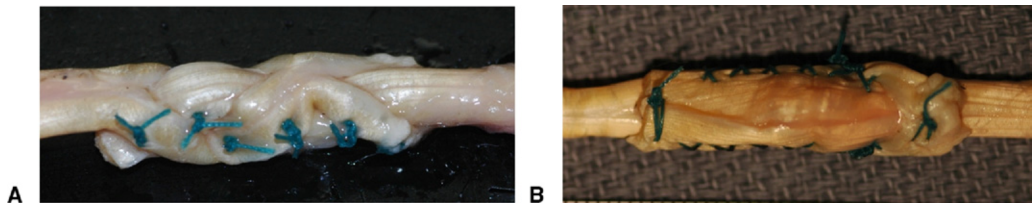

FIGURE 1: A The PT repair consists of the FDS weaving through 3 incisions in the FDP, one double-loop suture at each tendon free end, and 4 mattress sutures evenly spaced between (mattress sutures were made with 2 connection points between the tendons—one at the top of the loop and a second where the stitch was completed). **B** The SS repair consists of the FDS inserting through one incision in the FDP, 4 cross-stitch running sutures back and forth down both sides, and one double-loop suture at each tendon free end.

the mechanical testing apparatus. However, because the comparison was made between equivalent lengths, we did not consider this a fatal flaw in the experiment. Tendon cross-sectional area was calculated using the following equation:[14]

$$CSA(mm^2) = \frac{mass(g)}{\rho\left(\frac{g}{mm^3}\right) \times length(mm)}$$

where ρ=tendon density (0.00112 g/mm^3),[15] and mass and length were measured from small sections of the tendon free ends.

All mechanical tests were carried out using a tensile testing machine (Instron Model 1122; Instron, Norwood, MA). Clamps secured the tendons on each side of the repair, and specimens were mounted in a vertical orientation. Two small incisions were made at each free end of the tendons, and gauze was wrapped through these incisions and around the free ends to provide more holding strength within the clamps. Specimens were immersed in phosphate-buffered saline solution throughout the test. Slack length of the overall structure was established as the length just before the initiation of load resistance, based on the electronic noise of the force transducer. Repairs were tested in tension at a displacement rate of 10 mm/min. First, repairs were preconditioned with 5 consecutive cycles of 5% clamp-to-clamp displacement. At the end of the preconditioning cycles, repairs were allowed to stress-relax for approximately 25 seconds and then were elongated to failure. Peak loads in the preconditioning cycles were always less than the loads of first failure detection.

Repair deformation was quantified by video-tracking elastin dye lines placed on either side of the repair region. Variables measured were peak load during each of the 5 preconditioning cycles, load of first failure (first negative inflection of force during the failure test), ultimate load (highest force achieved during the failure test), and repair stiffness (slope of the linear region of the load-deformation curve) (Fig. 2). Statistical comparisons between SS and PT repair techniques were made using nonparametric Mann-Whitney U tests with a significance level (α) of 0.05.

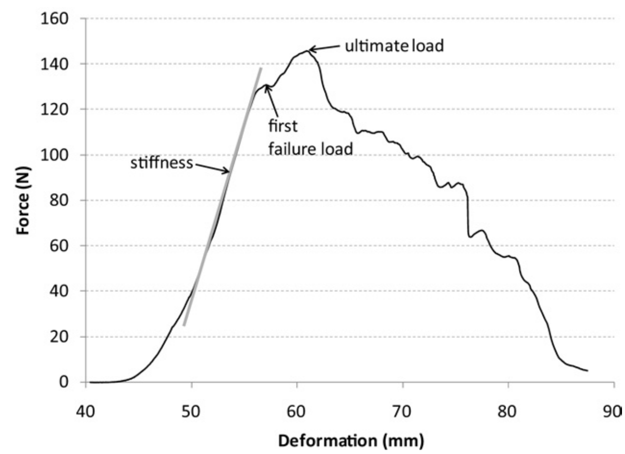

FIGURE 2: Representative force-deformation curve for a PT repair. Stiffness was calculated as the slope of the linear portion of the force-deformation curve.

RESULTS

There were no statistically significant differences in the cross-sectional area (p=.99) or initial deformation (distance between tracked elastin lines at slack length, p=.93) between SS and PT repairs. Therefore, all statistical comparisons were made between non-normalized loads and deformations (as opposed to stress and strain, which would be normalized to cross-sectional area and initial length, respectively).

All failures occurred in the repair region, rather than at the clamps or within the tendon substance. The PT repairs failed with suture knots either slipping or pulling through the tendon material, followed by the FDS tendon pulling through the FDP tendon. The SS repairs failed by the longitudinal shearing of fibers within the

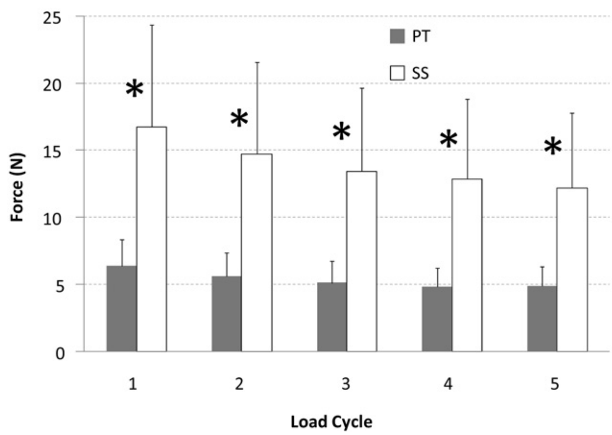

FIGURE 3: Mean load (N) reached at each the peak of each of the 5 conditioning cycles. A statistically significant difference (*) was found between SS and PT repairs at each cycle. Standard deviation bars are shown.

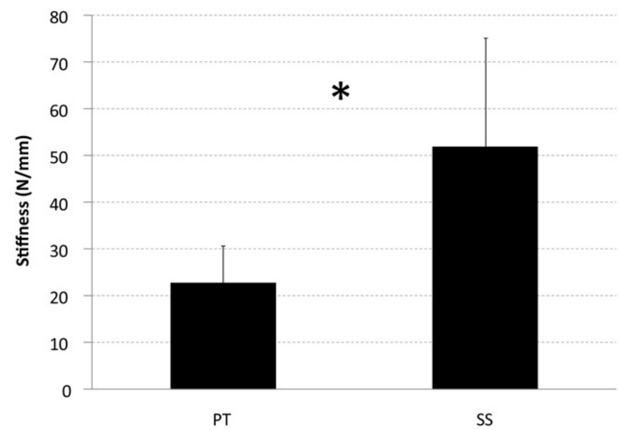

FIGURE 5: Mean stiffness (N/mm) for SS and PT repair techniques. The asterisk indicates a statistically significant difference between the 2 repair types. Standard deviation bars are shown.

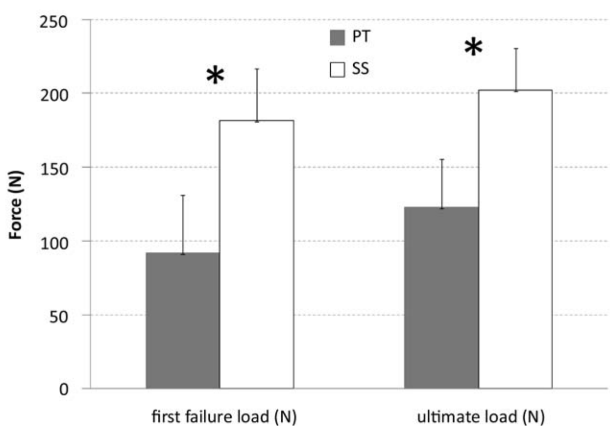

FIGURE 4: Mean first failure and ultimate loads (N) for SS and PT repair techniques. Asterisks indicate a statistically significant difference between the 2 repair types. Standard deviation bars are shown.

TABLE 2. First Failure Load, Ultimate Load, and Stiffness for Each Specimen

Specimen No.	Repair Type	First Failure Load (N)	Ultimate Load (N)	Stiffness (N/mm)
1	PT	145	162	25
2	PT	69	116	32
3	PT	131	146	19
4	PT	96	96	30
5	PT	55	140	20
6	PT	56	75	11
7	SS	180	180	30
8	SS	248	256	97
9	SS	205	209	33
10	SS	148	221	54
11	SS	159	184	65
12	SS	175	184	45
13	SS	154	180	38

FDS, whereby fibers that were locked down with the running sutures stayed attached to the FDP, and adjacent, non-locked-down fibers sheared away with the FDS.

Peak load during each of the conditioning displacement cycles (range $p=.005$ to $p=.01$, Fig. 3), load at first failure ($p=.001$), ultimate load ($p=.001$), and repair stiffness ($p=.001$) were all significantly different between SS and PT techniques; in all cases, the mean value for SS was higher than for PT (Figs. 3–5; Table 2).

DISCUSSION

This *in vitro* human cadaveric study demonstrated that the method of tendon repair used for musculotendinous transfer can influence the immediate strength of repair and, therefore, the ability to pursue postoperative rehabilitation protocols that use early motion. The main result of this study was that the SS suture method tested here produced significantly stronger ($p = .001$) and stiffer ($p = .001$) repairs compared to the tested variation of the PT repair. Originally, the SS technique was designed to provide sufficient mechanical strength to permit immediate contractile use of a transferred muscle after surgery.[11] Traditional clinical guidelines advocated a minimum of 3 weeks of immobilization after surgery,[6–10] but more recent guidelines have advocated early, active mobilization of tendon repairs, thereby increasing the need to implement a strong repair. In recent years, in tetraplegia surgery, the immediate postoperative activation of a transferred muscle using the SS repair has been implemented successfully in hundreds of clinical cases.[11] The current study provides mechanical justification that, at the time of repair, the SS repair using a cross-stitch technique is indeed stronger than this variation of the PT repair, using a mattress stitch technique, thereby providing a larger safety margin that provides assurance to surgeons who promote immediate loading of the repair site. This study is limited in that it was not designed to isolate the specific mechanisms (eg, suture-throw technique or tendon-weave technique) underlying the difference in strength and stiffness; future work will need to address this question.

Mean failure loads for both SS and PT repairs were greater than the estimated maximum isometric force that can be generated by the FDS muscle group.[16–17] Average first detected failure loads in the current study were 182 N and 92 N for SS and PT repairs, respectively, which provide safety factors (the relative difference between the estimated maximum load a muscle can produce and the strength of its tendon) of 2.64 and 1.33 times the estimated 69 N maximum load (calculated based on the architecture of these muscles).[17] This would appear to establish adequate margins of safety for both repair techniques. However, it is important to note that biological changes to tendon material occur immediately after surgery that can affect tendon repair strength.[18] Previous work demonstrated that tensile strength of *in vivo* end-to-end tendon repairs actually decreased for several days after surgery, before healing and strengthening takes effect,[18] although more recent work has found no change in strength over the first 3 weeks after repair.[19] From a safety perspective, the time course for the healing of tendon repairs must be considered, such that if strength declines during the first postoperative days, safety factors of the repairs can be compromised. Strength of the transferred muscle will generally decline also due to postoperative atrophy.[20] Thus, the time-varying nature of both tendon repair strength and muscular strength must be considered throughout the rehabilitation process. There exists no evidence as to whether such time-varying changes differ between the repair techniques studied here, and future work will need to address this issue. The much greater safety factor for the SS repair, in comparison to the PT repair, should be beneficial to maintain the repair failure threshold above the muscular applied loads during the early postoperative period.

Relatively little mechanical testing has been done to examine the tensile strength of repair techniques used in tendon transfers (for example, a Medline search using combinations of the key words tendon, transfer, strength, repair, and weave uncovered 5 papers[21–25] examining the mechanical strength of overlapping tendon to tendon repair techniques). Further, because of differences between studies regarding surgical techniques, suture material used, and testing procedures, it is often difficult to make direct comparisons. Three recent papers, with methods comparable to those of the current study, quantified the tensile strength of the PT repair technique. The ultimate load in each of these papers (106 ± 13 N, Kulikov et al.[21]; 102 ± 6 N, De Smet et al.[22]; 128 N [no standard deviation reported], Gabuzda et al.[23]) was comparable to the ultimate load for the technique quantified here (122 ± 33 N). Gabuzda et al.[23] compared PT weave using both mattress sutures and cross-stitch sutures, in identical locations, to join the tendons together. They found that the cross-stitch sutures increased the ultimate load of the repair by approximately 72%, to 220 N. This load is comparable to the ultimate load documented here for the SS repair technique (202 ± 29 N). Thus, it would appear that cross-stitch sutures considerably increase the strength of a tendon repair. Of the previously discussed studies, only Kulikov et al.[21] quantified PT repair stiffness and reported a value of 11 ± 1 N/mm, much lower than the stiffness documented here for either the PT (23 ± 8 N/mm) or SS (52 ± 23 N/mm) repair techniques. The large difference in PT stiffness might simply result from variations of the PT technique used between studies or in how deformation was measured. In the current study, deformation was measured across the repair site by tracking the movement of elastin dye lines on either side of the repair; Kulikov et al.[18] did not explicitly describe their measurement of deformation, but it appears that it included the deformation of both the repair region and the tendon material on either side of the repair region, which would yield a lower stiffness value. In the current study, the SS was significantly stiffer ($p = .001$) than the PT repair, which might be beneficial because it permits more efficient load transfer from donor muscle to recipient tendon and, ultimately, to the bony insertion site.

The SS technique consists of the donor tendon inserted through a single incision on the recipient, one double-loop suture at both ends of the overlap, and running cross-stitch sutures down both sides (Fig. 1). The PT technique consists of the donor tendon weaving through 3 incisions on the recipient, with a double-loop suture at both ends of the overlap and 4 mattress sutures evenly spaced between the 2 end sutures. Observation of the failure modes in each case demonstrated a consistent finding: The load resisted by the PT repair increased until one of the 6 stabilizing sutures failed, either by a knot slipping or by suture pull-out from the tendon material, thus causing an immediate drop in the load (first failure load). The resisted load then quickly recovered and increased until a second suture location failed, causing a second immediate drop in the load, which most often did not recover (ultimate load). Thus, it appeared that the sutures were loaded in an unbalanced manner, creating stress concentrations at individual suture–tissue interfaces. The SS repairs failed in an entirely different manner. The tendon material of the donor tendon appeared to separate longitudinally and slide apart, with the fibers locked with the running sutures staying attached to the recipient tendon and the adjacent, non-locked fibers pulling away with the donor. Thus, the running cross-stitch sutures acted to distribute the load over a wider suture–tissue interface, thus reducing stress concentration at individual sutures.

Numerous reports document that early passive[3] and active[1,2] mobilization of a transferred muscle reduces the incidence of adhesion formation, improves the recovery of joint range of motion, and reduces postoperative recovery time. Tendon end-to-end repair models have been shown to benefit from early motion and loading, with improved tensile strength,[4] vascularity, and cellularity.[5] A strong surgical repair is required in order to enable a patient to activate a transferred muscle and load the repair with a minimum risk of damaging the repair. The SS suture technique appears to meet these requirements based at time zero or immediately following repair, both from the mechanical evidence demonstrated here and from clinical experience.[13] There are a number of differences between the SS and PT repair techniques (Table 1), and our conclusions are limited to the specific variations tested here. Previous work[23] has shown that the primary difference improving the strength of the SS repair might be cross-stitch sutures rather than mattress sutures. Thus, stabilizing the PT repair with cross-stitch sutures might greatly improve its strength and stiffness, potentially matching that of the SS technique demonstrated here. Future work will be designed to specifically test this hypothesis.

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