

RESEARCH ARTICLE

Fine tuning of the side-to-side tenorrhaphy: A biomechanical study assessing different side-to-side suture techniques in a porcine tendon model

Christina J. Wilhelm¹✉*, Marc A. Englbrecht¹✉^{‡a}, Rainer Burgkart², Carina Micheler¹✉^{‡,3}, Jan Lang¹✉^{‡,4}, Christine S. Hagen¹✉^{‡b}, Riccardo E. Giunta¹, Nikolaus Wachtel¹

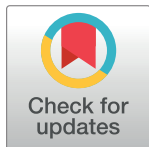
1 Division of Hand, Plastic and Aesthetic Surgery, University Hospital, LMU Munich, Munich, Germany, **2** Department of Orthopaedics and Sports Orthopaedics, Klinikum Rechts der Isar, School of Medicine, Technical University of Munich, Munich, Germany, **3** Department of Mechanical Engineering, Institute for Machine Tools and Industrial Management, Technical University of Munich, Munich, Germany, **4** Department of Mechanical Engineering, Chair of Non-Destructive Testing, Technical University of Munich, Munich, Germany

✉ These authors contributed equally to this work.

‡a Current address: SENO MVZ, Camparihaus Munich, Munich, Germany

‡b Current address: Frauenklinik Dr. Geisenhofer, Munich, Germany

* christina@wilhelm.nu



OPEN ACCESS

Citation: Wilhelm CJ, Englbrecht MA, Burgkart R, Micheler C, Lang J, Hagen CS, et al. (2021) Fine tuning of the side-to-side tenorrhaphy: A biomechanical study assessing different side-to-side suture techniques in a porcine tendon model. *PLoS ONE* 16(10): e0257038. <https://doi.org/10.1371/journal.pone.0257038>

Editor: Gabriel de Araújo, Universidade Federal Fluminense, BRAZIL

Received: June 21, 2021

Accepted: August 17, 2021

Published: October 5, 2021

Copyright: © 2021 Wilhelm et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the manuscript and its [Supporting information](#) files.

Funding: The authors received no specific funding for this work.

Competing interests: I have read the journal's policy and the authors of this manuscript have the following competing interests: M. A. E. works as an instructor for Arthrex Inc educational courses on a fee basis. No further external funding, payments, or

Abstract

Recent studies conclude that a new technique for tendon transfers, the side-to-side tenorrhaphy by Fridén (FR) provides higher biomechanical stability than the established standard first described by Pulvertaft (PT). The aim of this study was to optimize side-to-side tenorrhaphies. We compared PT and FR tenorrhaphies as well as a potential improvement, termed Woven-Fridén tenorrhaphy (WF), with regard to biomechanical stability. Our results demonstrate superior biomechanical stability and lower bulk of FR and, in particular, WF over PT tenorrhaphies. The WF and FR technique therefore seem to be a notable alternative to the established standard tenorrhaphy as they display lower bulk and higher stability, permitting successful immediate active mobilization after surgery.

Introduction

Tendon transfers with a subsequent side-to-side tenorrhaphy are predominantly used to restore limb-function after trauma of the central or peripheral nervous system and/or trauma impairing muscle (tendon) function of the extremities [1, 2]. This surgical technique is commonly performed in foot and ankle as well as in hand and plastic surgery. Common examples include the treatment of patients with common peroneal nerve palsy (foot drop) and insertional or noninsertional tendinopathy of the Achilles tendon [3, 4]. Moreover, side-to-side tenorrhaphies are used to restore critical grasping motions of the hand after brachial plexus palsy [5, 6].

services have been received or will be received from a commercial party related directly or indirectly to the subject of this article. The authors alone are responsible for experiments, data analysis, and writing of the paper. This does not alter our adherence to PLOS ONE policies on sharing data and materials.

Here, an optimal suture stability is essential, allowing for early mobilization and, thus, reduced adhesion formation and post-operative recovery time [7, 8]. The established standard technique for a tendon transfer was first described by Pulvertaft (PT) *et al.* [9–11]. Interestingly, recent studies demonstrated that a new technique, the side-to-side tenorrhaphy by Fridén (FR) *et al.*, provides both efficient force transmission and high suture strength. Indeed, repair stiffness, load at first failure and ultimate failure load of the FR suture were significantly higher when compared to PT sutures [7, 8, 12, 13].

The aim of this biomechanical study was therefore to optimize the technique of side-to-side tenorrhaphies. We assessed the biomechanical properties of PT, FR, and a potential improvement of the FR technique, termed Woven-Fridén (WF) tenorrhaphy.

Materials and methods

Ethics statement

Ethical approval for this study was obtained from the Ethics Committee of the Medical Faculty at LMU Munich, Germany (Approval Number: 19–142). Tendons were obtained from porcine hind limbs. These were purchased from a local butcher. The Ethics Committee for Animal Experiments, LMU Munich, granted a formal waiver for current and future experiments using tendons from porcine hind limbs.

Inclusion, exclusion and randomization

The extensor tendons of porcine hind limbs were harvested as previously described by Fuchs *et al.* [14]. After harvesting, tendons were stored in a vacuum bag and fresh-frozen at -28°C . Specimens were thawed in water at 37°C directly before performing the sutures [15, 16]. Block randomization was used to determine which tendon pairs were used in experimental groups and to distribute the tendons of each limb to the three groups of one experimental series in a balanced manner (S1 Data). For each experimental group, 12 side-to-side tenorrhaphies were tested. Thus, a total of 72 sutures were tested.

Tenorrhaphies

PT and FR tenorrhaphies were performed as described previously by Brown *et al.* [7] (Fig 1). Additionally, we tested a varied approach to the FR technique, termed WF (Fig 2). Each tenorrhaphy was performed with a 30 mm tendon-tendon overlap. Ethibond™ 3–0 (Ethicon, Inc. Somerville, NJ, USA) was used as suture material.

Suture characteristics and biomechanical testing

Tendon and suture diameter as well as the length of overlap were measured with a digital caliper after tenorrhaphy completion. The bulk ratio of tenorrhaphies was determined by dividing the cross-sectional area of tendons [13]. For biomechanical testing, stiffness (resistance of sutures to deformation), first failure load (first local maximum of force in the load-deformation curve), and ultimate load (highest force (N) achieved before ultimate failure) were measured as described previously [7, 12, 13, 17].

All experiments were performed following a standardized protocol, similar to protocols of previous studies [7, 12, 17]. All mechanical tests were performed using a calibrated tensile testing machine (Zwicki 1120, ZwickRoell GmbH & Co. KG, Ulm, Baden-Württemberg, Germany). A preload of 2 N was applied to minimize slack and 5 preconditioning cycles with a deformation of 5% of the distance between the clamps were imposed [7, 18]. Tenorrhaphies were then preconditioned at a velocity of 10 mm/min to be elongated until failure at a velocity

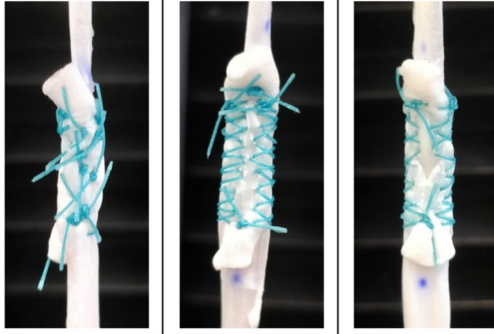
	PT	FR	WF
Number of weaves	3 (2 horizontal, 1 vertical)	1	3 (all horizontal)
Locking suture	2 double-loop sutures	2 double-loop sutures	2 double-loop sutures
Fixing suture	8 mattress sutures	16 running cross-stitches	16 running cross-stitches
Connection points	18	18	18
Overview			

Fig 1. Overview of suture techniques used. The different techniques Pulvertaft (PT), Fridén (FR) and Woven-Fridén (WF) are illustrated: The donor tendon (above) was woven through incisions in the recipient tendon (below). For each suture technique the same amount of connection points between the tendons was used. The threads were cut in standardized fashion at 10 mm length.

<https://doi.org/10.1371/journal.pone.0257038.g001>

of 100 mm/min [7, 12, 17]. The tensile load test outputs were plotted on a load-deformation curve (TestXpert V12.0 ZwickRoell GmbH & Co. KG, Ulm, Baden-Württemberg, Germany). We used a custom written MATLAB code (MATLAB R2017b, The MathWorks, Inc. Natick, MA, USA) to determine load at first failure, ultimate load and repair stiffness. The stiffness of the tenorrhaphy was determined within the linear elastic area of the load-deformation curve. The preconditioning data were removed and by means of the coefficient of determination (R^2), the linear elastic area was identified to calculate the stiffness of the tenorrhaphy [19]. Means and standard deviations were calculated for the different groups. Tensile testing was filmed using a Legria HF M31 video camera (Canon Co. Ltd., Ohta-ku, Tokyo, Japan) to document the mode of failure (pull-out vs. suture breakage) [20, 21].

Statistical analysis

Data are given as means and standard deviation (SD). One-way analysis of variance (ANOVA), followed by the Tukey-Kramer test for multiple comparisons was conducted to assess effects of tenorrhaphy techniques on bulk ratio, repair stiffness, first failure load, and ultimate load. A p -value of < 0.05 was considered statistically significant. GraphPad Prism 6 (GraphPad Software, Inc., San Diego, CA, USA) was used as software for statistical analysis.

Results

When analyzing different tenorrhaphy techniques, the WF group had the lowest relative cross-sectional area (bulk ratio), which was significantly lower when compared to the PT group ($p < 0.001$) (Fig 3). Results for biomechanical analysis of different tenorrhaphies are shown in Fig 4. Ultimate load was highest in the WF group (compared to both FR and PT tenorrhaphies; p of 0.02 and < 0.001 , respectively). Stiffness was highest for WF and FR sutures ($p = 0.005$ for PT vs. FR and $p < 0.001$ for PT vs. WF). WF sutures therefore showed highest stability while suture failure occurred earliest in the PT technique. All side-to-side tenorrhaphies failed by

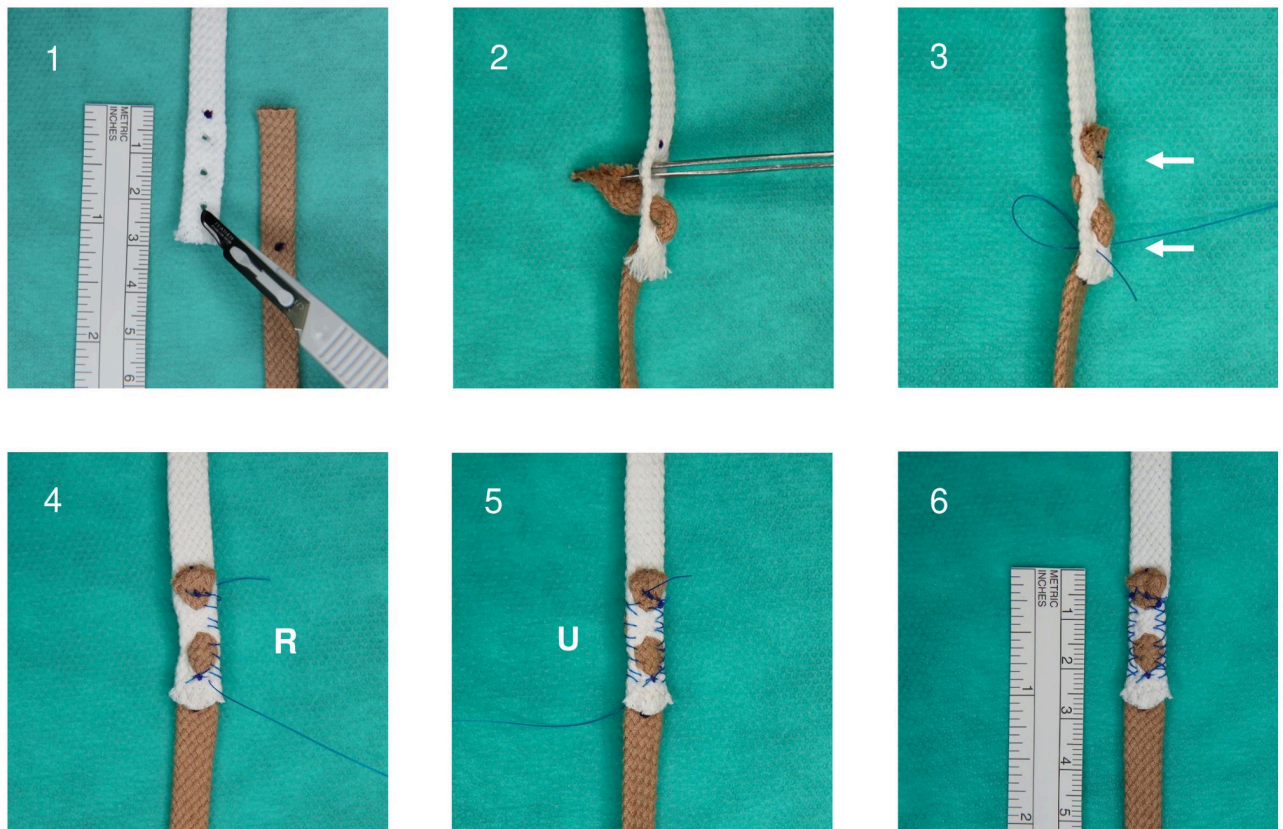


Fig 2. Schematic model of the Woven-Fridén tenorrhaphy (WF) (30 mm tendon-tendon overlap) using brown and white strings. 1. Mark incisions and overlap for donor- (brown) and recipient tendon (white) with a surgical pen and make three incisions in the recipient tendon using a No. 15 scalpel blade. 2. Interlace the donor tendon (brown) through the recipient tendon (white). 3. Perform two double-loop sutures at proximal and distal end of tenorrhaphy (arrows). 4. Perform eight running cross stitches at the radial side (R) and 5. ulnar side (U) of the tenorrhaphy. 6. WF tenorrhaphy (the overlap has been reduced to approximately 27 mm due to interlacing of tendons).

<https://doi.org/10.1371/journal.pone.0257038.g002>

pull-out. For all experiments, first failure load was identical or highly similar to ultimate failure load (also see [S1 Data](#)).

Discussion

In our study, we set out to determine the biomechanical properties of the FR side-to-side tenorrhaphy, which was recently proposed as an alternative to PT sutures with superior biomechanical stability [7, 12, 13]. Furthermore, we aimed to improve the FR technique by adding two horizontal weaves (Fig 2). We termed this variation WF.

A high bulk of tendon-to-tendon sutures can lead to friction between tendons and adjacent tissue. This results in formation of adhesions that compromise the natural gliding mechanics of tendons [18, 22–24]. Moreover, a strong mechanical tenorrhaphy is essential for an optimal clinical outcome as it permits immediate active mobilization thereby minimizing adhesion formation and providing optimal conditions for healing and mobility [8, 25]. Recent studies with a similar set-up demonstrated that the ultimate load of the FR technique was significantly higher when compared to PT sutures [7, 12, 13]. We were able to confirm these findings (Fig 4). Moreover, the highest ultimate failure load and lowest bulk formation was measured for the WF group (Figs 3 and 4). The findings of this study therefore advocate an advantage of FR

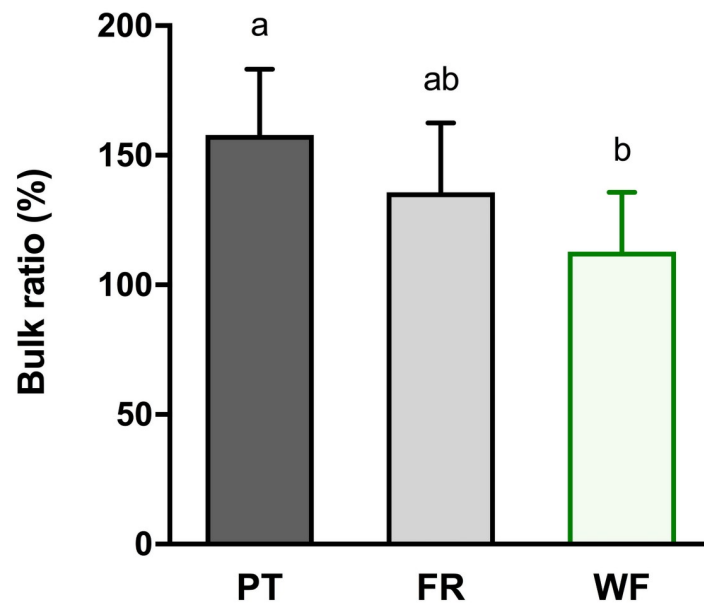


Fig 3. Effects of suture techniques Pulvertaft (PT), Fridén (FR) and Woven-Fridén (WF) on bulk ratio in % (ratio of the cross-sectional area of the sutured tendons and the native tendons; for details see S1 Data). Data is expressed as means, standard deviation bars are shown. Different superscripts indicate statistically significant differences among groups at $p < 0.001$. For each experimental group, 12 side-to-side tenorrhaphies were tested.

<https://doi.org/10.1371/journal.pone.0257038.g003>

and, in particular, WF side-to-side tenorrhaphies over the technique described by PT with regard to biomechanical stability as well as bulk.

A probable explanation for the higher stiffness and load bearing capacities of both FR and WF tenorrhaphies is the usage of running cross-stitches for both techniques. An advantage of

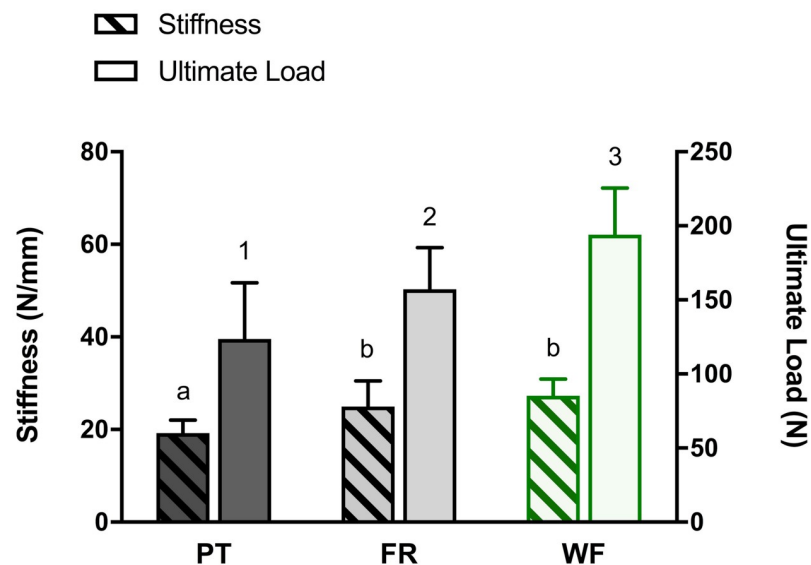


Fig 4. Effects of suture techniques Pulvertaft (PT), Fridén (FR) and Woven-Fridén (WF) on stiffness (resistance of sutures to deformation) in N/mm (crosshatched bars) and on ultimate load in N (single-colour bars). Data is expressed as means, standard deviation bars are shown. Different superscripts indicate statistically significant differences among groups at $p < 0.05$ and for WF vs. PT at $p < 0.0001$. For each experimental group, 12 side-to-side tenorrhaphies were tested.

<https://doi.org/10.1371/journal.pone.0257038.g004>

these stitches seems likely as all three suture techniques had the same number of connection points (Fig 1). Indeed, a previous biomechanical study demonstrated the superior ultimate load bearing capacities of cross-stitches over mattress sutures [26]. Equally, Brown *et al.* argue that running cross-stitches permit force distribution over a larger area when compared to mattress sutures used in the PT technique [7]. The mattress suture in the PT tenorrhaphy that is tightest might act as a focused transmission of tensile load from one tendon to the next and, thus, could facilitate suture failure. Differences between WF and FR sutures may be explained by a similar mechanism: more than one weave results in a more balanced load of force in combination with a stabilizing interlocking effect between the two tendons [4]. Hereby increasing the ultimate load of WF tenorrhaphies. However, if these hypotheses prove to be correct, it has to be argued whether the usage of cross-stitches instead of mattress sutures improves the biomechanical properties of the PT suture. Thus, matching those of FR or even WF tenorrhaphies.

The conclusions of this study are predominantly limited by its *in vitro* set-up. Porcine extensor tendons differ from human tendons in size and structure and our findings on load bearing capacity may therefore differ in human tendons, in particular when tendons with a different caliber are used [14, 27–31]. Moreover, by using a cadaver model we were unable to reproduce normal tissue biology. During the healing process with a subsequent inflammatory stage, the stability of the sutured tendons is reported to decline [32, 33]. Indeed, several studies that assessed the stability of tendon sutures *in vivo* during the healing period indicate that tensile strength of sutured tendons decreases during the first weeks postoperatively [34, 35]. High suture stability *in vitro* may therefore not ensure equal biomechanical properties *in vivo*. Being aware of this limitation, we advocate for subsequent studies that assess the three sutures in an *in vivo* set-up similar to previous publications that explored tendon biology [36–38].

This study demonstrated the superior biomechanical properties of FR side-to-side tenorrhaphies over PT sutures. Additionally, our proposed modifications of the FR technique, termed WF tenorrhaphy, further improved load bearing capacities. FR and, in particular, WF tenorrhaphies therefore seem to be a superior alternative to the established standard technique for side-to-side tenorrhaphies, thereby increasing probability of successful immediate active mobilization after surgery.

Supporting information

S1 Table. Standardized experimental protocol using block randomization. A-C stand for Pulvertaft (PT), Fridén (FR) and Woven-Fridén (WF) suture techniques. Four tendons of porcine hind limbs were used: M. extensor digitalis lateralis (I), M. extensor digiti III et IV (II) M. extensor digiti III (III) and M. extensor digiti I longus (IV). Tendons were cut in half before combining the proximal part (prox.) of one tendon with the distal part (dist.) of another tendon for a suture. The lateral (I) and the medial tendon (IV) had a smaller caliber and were therefore used as donors, median tendons (II and III) were used as recipients. Every combination of donor- and recipient-tendon was equally often used for each experimental group. (DOCX)

S2 Table. Comparison of different characteristics of three different suture techniques: Pulvertaft (PT), Fridén (FR) and Woven-Fridén (WF). Values are expressed as mean (SD). Different superscripts indicate statistically significant differences among groups at p of at least < 0.05 . (DOCX)

S1 File. Calculation of the Bulk Ratio (BR). The formula to calculate the BR is given and derived.

(DOCX)

S1 Data. Tabular listing and graphical representation of all collected data.

(PDF)

Author Contributions

Conceptualization: Marc A. Englbrecht, Christine S. Hagen, Nikolaus Wachtel.

Data curation: Carina Micheler, Jan Lang.

Formal analysis: Christina J. Wilhelm.

Investigation: Christina J. Wilhelm.

Methodology: Christina J. Wilhelm, Marc A. Englbrecht, Carina Micheler, Jan Lang, Nikolaus Wachtel.

Project administration: Nikolaus Wachtel.

Resources: Rainer Burgkart, Riccardo E. Giunta.

Software: Carina Micheler, Jan Lang.

Supervision: Marc A. Englbrecht, Rainer Burgkart, Christine S. Hagen, Riccardo E. Giunta.

Validation: Carina Micheler, Jan Lang, Nikolaus Wachtel.

Visualization: Christina J. Wilhelm, Nikolaus Wachtel.

Writing – original draft: Christina J. Wilhelm.

Writing – review & editing: Riccardo E. Giunta, Nikolaus Wachtel.

References

1. Wilbur D, Hammert WC. Principles of Tendon Transfer. *Hand clinics*. 2016; 32(3):283–9. <https://doi.org/10.1016/j.hcl.2016.03.001> PMID: 27387072
2. Fitoussi F, Bachy M. Tendon lengthening and transfer. *Orthopaedics & traumatology, surgery & research: OTSR*. 2015; 101(1 Suppl):S149–57. <https://doi.org/10.1016/j.otsr.2014.07.033> PMID: 25572471
3. Marsland D, Stephen JM, Calder T, Amis AA, Calder JDF. Strength of Interference Screw Fixation to Cuboid vs Pulvertaft Weave to Peroneus Brevis for Tibialis Posterior Tendon Transfer for Foot Drop. *Foot & ankle international*. 2018; 39(7):858–64. <https://doi.org/10.1177/1071100718762442> PMID: 29582684
4. Wagner E, Ortiz C, Wagner P, Guzman R, Ahumada X, Maffulli N. Biomechanical evaluation of various suture configurations in side-to-side tenorrhaphy. *The Journal of bone and joint surgery American volume*. 2014; 96(3):232–6. <https://doi.org/10.2106/JBJS.L.01552> PMID: 24500585
5. Abzug JM, Kozin SH. Evaluation and management of brachial plexus birth palsy. *The Orthopedic clinics of North America*. 2014; 45(2):225–32. <https://doi.org/10.1016/j.ocl.2013.12.004> PMID: 24684916
6. Gutowski KA, Orenstein HH. Restoration of elbow flexion after brachial plexus injury: the role of nerve and muscle transfers. *Plastic and reconstructive surgery*. 2000; 106(6):1348–57; quiz 58; discussion 59. <https://doi.org/10.1097/00006534-200011000-00020> PMID: 11083569
7. Brown SH, Hentzen ER, Kwan A, Ward SR, Friden J, Lieber RL. Mechanical strength of the side-to-side versus Pulvertaft weave tendon repair. *J Hand Surg Am*. 2010; 35(4):540–5. <https://doi.org/10.1016/j.jhsa.2010.01.009> PMID: 20223604
8. Friden J, Reinholdt C. Current concepts in reconstruction of hand function in tetraplegia. *Scandinavian journal of surgery: SJS: official organ for the Finnish Surgical Society and the Scandinavian Surgical Society*. 2008; 97(4):341–6. <https://doi.org/10.1177/145749690809700411> PMID: 19211389

9. Pulvertaft RG. Tendon grafts for flexor tendon injuries in the fingers and thumb; a study of technique and results. *The Journal of bone and joint surgery British volume*. 1956; 38-b(1):175–94. <https://doi.org/10.1302/0301-620X.38B1.175> PMID: 13295327
10. De Smet L, Schollen W, Degreef I. In vitro biomechanical study to compare the double-loop technique with the Pulvertaft weave for tendon anastomosis. *Scandinavian journal of plastic and reconstructive surgery and hand surgery*. 2008; 42(6):305–7. <https://doi.org/10.1080/02844310802401330> PMID: 18991173
11. Cheah AE, Etcheson J, Yao J. Radial Nerve Tendon Transfers. *Hand clinics*. 2016; 32(3):323–38. <https://doi.org/10.1016/j.hcl.2016.03.003> PMID: 27387076
12. Tsiampa VA, Ignatiadis I, Papalois A, Givissis P, Christodoulou A, Friden J. Structural and mechanical integrity of tendon-to-tendon attachments used in upper limb tendon transfer surgery. *Journal of plastic surgery and hand surgery*. 2012; 46(3–4):262–6. <https://doi.org/10.3109/2000656X.2012.684097> PMID: 22616803
13. Rivlin M, Eberlin KR, Kachooei AR, Hosseini A, Zivaljevic N, Li G, et al. Side-to-Side Versus Pulvertaft Extensor Tenorrhaphy—A Biomechanical Study. *The Journal of hand surgery*. 2016; 41(11):e393–e7. <https://doi.org/10.1016/j.jhsa.2016.07.106> PMID: 27546442
14. Fuchs SP, Walbeehm ET, Hovius SE. Biomechanical evaluation of the Pulvertaft versus the 'wrap around' tendon suture technique. *The Journal of hand surgery, European volume*. 2011; 36(6):461–6. <https://doi.org/10.1177/1753193411402756> PMID: 21447532
15. Viidik A, Lewin T. Changes in tensile strength characteristics and histology of rabbit ligaments induced by different modes of postmortal storage. *Acta orthopaedica Scandinavica*. 1966; 37(2):141–55. <https://doi.org/10.3109/17453676608993274> PMID: 5911489
16. Giannini S, Buda R, Di Caprio F, Agati P, Bigi A, De Pasquale V, et al. Effects of freezing on the biomechanical and structural properties of human posterior tibial tendons. *International orthopaedics*. 2008; 32(2):145–51. <https://doi.org/10.1007/s00264-006-0297-2> PMID: 17216243
17. Friden J, Tirrell TF, Bhola S, Lieber RL. The mechanical strength of side-to-side tendon repair with mismatched tendon size and shape. *The Journal of hand surgery, European volume*. 2015; 40(3):239–45. <https://doi.org/10.1177/1753193413517327> PMID: 24413573
18. Jeon SH, Chung MS, Baek GH, Lee YH, Kim SH, Gong HS. Comparison of loop-tendon versus end-weave methods for tendon transfer or grafting in rabbits. *The Journal of hand surgery*. 2009; 34(6):1074–9. <https://doi.org/10.1016/j.jhsa.2009.02.025> PMID: 19643292
19. Synek A, Chevalier Y, Baumbach SF, Pahr DH. The influence of bone density and anisotropy in finite element models of distal radius fracture osteosynthesis: Evaluations and comparison to experiments. *Journal of biomechanics*. 2015; 48(15):4116–23. <https://doi.org/10.1016/j.jbiomech.2015.10.012> PMID: 26542787
20. Miller B, Dodds SD, deMars A, Zagoreas N, Waitayawinyu T, Trumble TE. Flexor tendon repairs: the impact of fiberwire on grasping and locking core sutures. *The Journal of hand surgery*. 2007; 32(5):591–6. <https://doi.org/10.1016/j.jhsa.2007.03.003> PMID: 17481994
21. Barrie KA, Tomak SL, Cholewicki J, Merrell GA, Wolfe SW. Effect of suture locking and suture caliber on fatigue strength of flexor tendon repairs. *The Journal of hand surgery*. 2001; 26(2):340–6. <https://doi.org/10.1053/jhsu.2001.22926> PMID: 11279582
22. Amadio PC. Friction of the gliding surface. Implications for tendon surgery and rehabilitation. *Journal of hand therapy: official journal of the American Society of Hand Therapists*. 2005; 18(2):112–9. <https://doi.org/10.1197/j.jht.2005.02.005> PMID: 15891969
23. Rawson S, Cartmell S, Wong J. Suture techniques for tendon repair; a comparative review. *Muscles, ligaments and tendons journal*. 2013; 3(3):220–8. PMID: 24367784
24. Graham JG, Wang ML, Rivlin M, Beredjikian PK. Biologic and mechanical aspects of tendon fibrosis after injury and repair. *Connective tissue research*. 2019; 60(1):10–20. <https://doi.org/10.1080/03008207.2018.1512979> PMID: 30126313
25. Wangdell J, Bunketorp-Kall L, Koch-Borner S, Friden J. Early Active Rehabilitation After Grip Reconstructive Surgery in Tetraplegia. *Archives of physical medicine and rehabilitation*. 2016; 97(6 Suppl): S117–25. <https://doi.org/10.1016/j.apmr.2015.09.025> PMID: 27233586
26. Gabuzda GM, Lovallo JL, Nowak MD. Tensile strength of the end-weave flexor tendon repair. An in vitro biomechanical study. *Journal of hand surgery (Edinburgh, Scotland)*. 1994; 19(3):397–400. [https://doi.org/10.1016/0266-7681\(94\)90098-1](https://doi.org/10.1016/0266-7681(94)90098-1) PMID: 8077837
27. Mao WF, Wu YF, Zhou YL, Tang JB. A study of the anatomy and repair strengths of porcine flexor and extensor tendons: are they appropriate experimental models? *The Journal of hand surgery, European volume*. 2011; 36(8):663–9. <https://doi.org/10.1177/1753193411414117> PMID: 21768214

28. Haddad RJ Jr., Kester MA, McCluskey GM, Brunet ME, Cook SD. Comparative mechanical analysis of a looped-suture tendon repair. *The Journal of hand surgery*. 1988; 13(5):709–13. [https://doi.org/10.1016/s0363-5023\(88\)80130-8](https://doi.org/10.1016/s0363-5023(88)80130-8) PMID: 3071546
29. Savage R. In vitro studies of a new method of flexor tendon repair. *Journal of hand surgery (Edinburgh, Scotland)*. 1985; 10(2):135–41. [https://doi.org/10.1016/0266-7681\(85\)90001-4](https://doi.org/10.1016/0266-7681(85)90001-4) PMID: 3161963
30. Viinikainen A, Goransson H, Huovinen K, Kellomaki M, Tormala P, Rokkanen P. The strength of the 6-strand modified Kessler repair performed with triple-stranded or triple-stranded bound suture in a porcine extensor tendon model: an ex vivo study. *The Journal of hand surgery*. 2007; 32(4):510–7. <https://doi.org/10.1016/j.jhsa.2007.01.010> PMID: 17398362
31. Kulikov YI, Dodd S, Gheduzzi S, Miles AW, Giddins GE. An in vitro biomechanical study comparing the spiral linking technique against the pulvertaft weave for tendon repair. *The Journal of hand surgery, European volume*. 2007; 32(4):377–81. <https://doi.org/10.1016/J.JHSB.2007.02.009> PMID: 17452067
32. Voleti PB, Buckley MR, Soslowsky LJ. Tendon healing: repair and regeneration. *Annual review of biomedical engineering*. 2012; 14:47–71. <https://doi.org/10.1146/annurev-bioeng-071811-150122> PMID: 22809137
33. Hope M, Saxby TS. Tendon healing. *Foot and ankle clinics*. 2007; 12(4):553–67, v. <https://doi.org/10.1016/j.fcl.2007.07.003> PMID: 17996614
34. Wagner WF Jr., Carroll Ct, Strickland JW, Heck DA, Toombs JP. A biomechanical comparison of techniques of flexor tendon repair. *The Journal of hand surgery*. 1994; 19(6):979–83. [https://doi.org/10.1016/0363-5023\(94\)90101-5](https://doi.org/10.1016/0363-5023(94)90101-5) PMID: 7876500
35. Mason ML, Allen HS. THE RATE OF HEALING OF TENDONS: AN EXPERIMENTAL STUDY OF TENSILE STRENGTH. *Annals of surgery*. 1941; 113(3):424–59. <https://doi.org/10.1097/00000658-194103000-00009> PMID: 17857746
36. Dogramaci Y, Uruc V, Ozden R, Duman IG, Kalaci A, Altug ME, et al. The comparison of macroscopic and histologic healing of side-to-side (SS) tenorrhaphy technique and primer tendon repair in a rabbit model. *Archives of orthopaedic and trauma surgery*. 2014; 134(7):1031–5. <https://doi.org/10.1007/s00402-014-2010-z> PMID: 24853959
37. Wu YF, Zhou YL, Mao WF, Avanesian B, Liu PY, Tang JB. Cellular apoptosis and proliferation in the middle and late intrasynovial tendon healing periods. *J Hand Surg Am*. 2012; 37(2):209–16. <https://doi.org/10.1016/j.jhsa.2011.10.049> PMID: 22209211
38. Lui PP, Cheuk YC, Hung LK, Fu SC, Chan KM. Increased apoptosis at the late stage of tendon healing. *Wound repair and regeneration: official publication of the Wound Healing Society [and] the European Tissue Repair Society*. 2007; 15(5):702–7.