Strength of side-to-side and step-cut repairs in tendon transfers: biomechanical testing of porcine flexor tendons

E. Strandenes[1*], P. Ellison[2,3], A. Mølster[3,5], N.R. Gjerdet[4], I.O. Moldestad[3], P.J. Høl[3,5]

1. Plastic-, Hand- and Reconstructive Department, Haukeland University Hospital, Bergen, Norway

2. Department of Mechanical Engineering, Imperial College London, UK

3. Biomatlab, Department of Orthopaedic Surgery, Haukeland University Hospital, Bergen, Norway

4. Department of Clinical Dentistry, Faculty of Medicine, University of Bergen, Norway

5. Department of Clinical Medicine, Faculty of Medicine, University of Bergen, Norway

*Corresponding author: Eivind Strandenes, MD. Plastic-, Hand- and Reconstructive Department, Haukeland University Hospital. Tel. +47 55972771. Email: edss@helse-bergen.no. Twitter: @eivind_str

Keywords: tendon transfer; side-to-side; step-cut; biomechanics; tensile strength; tetraplegia; in vitro.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding statement

The authors received no financial support for the research, authorship, and/or publication of this article.

Ethics

No ethical approvals were needed since the tendons were obtained from pigs at a local butchery

ABSTRACT

The aim of the study was to compare side-to-side with step-cut repairs to determine how much of the width it is possible to remove and still keep the repair strong enough to start active mobilization. Porcine flexor tendons were used to create side-to-side, one-third step-cut and half step-cut repairs. There were 15 repairs in each group. The tensile properties of the constructs were measured in a biomechanical testing machine. All repairs failed by the sutures splitting the tendon longitudinally. The maximum load and stiffness were highest in the side-to-side group. Our findings suggest that the half step-cut repair can withstand the forces exerted during active unrestricted movement of the digits in tendons of this size. The advantage of the step-cut repair is reduced bulkiness and less friction, which might compensate for the difference in strength.

INTRODUCTION

Tendon transfer is used to restore hand function after nerve and tendon injuries. With this technique a tendon-muscle complex is sacrificed to provide power for a more valuable function. The technique is also used to improve hand function in tetraplegic patients with few functioning muscles. Modern rehabilitation protocols rely on a strong and stiff tendon repair to allow early active motion as we know this improves healing and remodelling of the tendon structure as well as reducing joint stiffness and oedema (Gelberman et al., 1981 and 1983). The Pulvertaft weave (Pulvertaft, 1956) has proven to be reliable but a concern is the bulkiness and the low stiffness of the repair. The low stiffness can make it difficult to determine the tension when transferring a tendon. The technique of bevelling the tendon was used in primary flexor tendon surgery to prevent gap formation (Becker and Davidoff, 1977) and was the precursor of the side-to-side technique in tendon transfer (Bidic et al., 2009; Brown et al., 2010). There are several studies comparing side-to-side tendon repair with other techniques, mainly the Pulvertaft technique (Bidic et al., 2009; Brown et al., 2010; Fridén et al., 2015; Fuchs et al., 2011; Rivlin et al., 2016). The side-to-side tendon repair has proven to be reliable and strong enough to start immediate range of motion (ROM) exercise. One of the advantages is the high stiffness of the technique (Brown et al., 2010). In a previous study a variation of the side-to-side technique, preserving two-thirds of the tendon width was compared with the Pulvertaft weave (Hashimoto et al., 2012), and the strength was found to be comparable.

Most tendon transfers rely on a segment where the tendons overlap. The cross-section at the repair site is usually larger than the intact tendon, causing increased friction and gliding resistance. One way to reduce the bulkiness is to apply a step-cut variant of the side-to-side repair (Hashimoto et al., 2012). To our knowledge there are no studies that compare side-to-side tendon repair with the step-cut variant. In this study one- third step-cut and half step-cut repairs were compared with side-to-side suture as a reference. The aim of this study was to determine by how much the thickness of tendons could be reduced and still obtain sufficient strength for immediate active mobilization.

METHODS

Flexor digitorum profundus (FDP) tendons from pigs were used in the experiments. Only the tendons from the second and third ray of the forelimbs were selected. The tendons were obtained from 1-year old pigs at a local butchery. We choose tendons from pig trotters since they have been found to have biomechanical characteristics that are similar to human flexor tendons (Hausmann et al., 2009; Havulinna et al., 2011; Mao et al., 2011).

Ninety FDP tendons were harvested to create 45 repairs. The tendons were stored in 0.9% NaCl and frozen until the experiment. Before the biomechanical testing the tendons were thawed at 4°C for 36 hours.

The tendons were allocated to three groups (n =15 in each group): standard side-to-side configuration (Brown et al., 2010), one-third step-cut, and half step-cut. The overlap was 3.5 cm in all groups.

The side-to-side group consisted of tendons sutured without any reduction of the cross section of the tendons (Figure 1A). In the step-cut groups one-third (Figure 1B) (Hashimoto et al., 2012) and one half (Figure 1C), respectively, of the cross-section was removed longitudinally. All tendon repairs were done with 3-0 braided non-absorbable sutures (Ethibond Excel, Ethicon Johnson & Johnson, Somerville, NJ, USA). Five continuous cross-stitches were placed at each side in the repair zone. In total ten cross-stitches were placed at an overlapping region of 3.5 cm (Figure 1). All repairs were done by the first author (E. S.).

The cross-sectional areas (A) was determined in the unoperated part of the tendons (two measurements) and in the overlapping area (three measurements). The areas were calculated by the formula $A= \pi*W*H/4$, where the width (W) and height (H) were taken from photographs (Table 1).

The specimens were kept moist with saline at room temperature (21-23°C).

Tensile testing

Tensile properties of the constructs were measured in a mechanical testing machine (Instron 5966; Instron Corp, Canton, MA, USA) with a custom-made grip (Shi et al., 2012). During testing the specimens were recorded with a video camera, which was part of the testing system (Instron advanced video recorder; Instron Corp, Canton, MA, USA). From the video we recorded elongation of the tendons. An additional camera (Sony α55; Sony Corp., Tokyo, Japan) recorded the testing in order to obtain detailed information about the failure mechanism.

The gauge length was 6.5 cm. Crosshead speed was 25 mm/minute and continued until failure, defined as the point where the load reached a maximum. From the resulting load-extension data maximum load, loads at 5 and 10 mm elongation and maximum stiffness, were calculated. Maximum stiffness was determined from the tangent of the steepest part of the load-extension curve.

Statistical methods

Power analysis based on pilot experiments indicated that 15 repeats of each experiment were needed (β=0.8). The arithmetic means and standard deviations were calculated. One-way ANOVA and post hoc multiple comparisons with Tukey corrections were used to analyse differences in ultimate strength and tendon cross-section areas between the three side-to-side variations. A p-value < 0.05 was considered to be statistically significant.

RESULTS

The cross-sectional areas of all the tendons were not statistically different outside the overlapped region (p=0.94). The side-to-side overlap region had a larger cross-sectional area than the two step-cut repairs (p<0.0001) (Table 1). The half step-cut overlap had a cross-sectional area close to the intact tendon.

Video recording of the test procedure revealed that all tendons failed at the repair site. There was no loosening at the clamps or tendon rupture at the end of the repair site. The mode of failure was that the sutures were pulled through the tendon, splitting the fibres longitudinally. In the side-to-side and one-third step cut the sutures were mainly pulled through at both suture rows (Figure 2A). No sutures ruptured. In the half step-cut 11 of the repairs failed by sutures being pulled through only one side (Figure 2B). The rest failed as in the two former groups. The mode of failure did not correlate with the strength of the repair in either groups.

The maximum load in the side-to-side group was the highest, followed by the one-third step-cut (p<0.05) and half step-cut (p<0.005) (Figure 3). There was no statistical difference between the two step-cut variations.

There was no statistical difference in maximum stiffness in the three groups (Table 1). The load at maximum stiffness (p<0.01) and 10 mm elongation (p=0.03) was higher for the side-to-side group compared with the half step-cut group. There was no statistical difference in the load at 5 mm elongation for the step-cut modifications compared with the side-to-side repair (Table 1).

DISCUSSION

The aim of this study was to assess by how much the tendon width can be reduced at the overlap region and still obtain a repair strong enough to allow immediate active mobilization. The ultimate load decreased with reduced cross-section of the repair zone, with the side-to-side as the strongest. Probably the reason is that the sutures have more tendon fibres to grasp in the side-to-side group than in the step-cut groups. The width of the suture grasps is the same but because of the step-cut the thickness of the tendon is reduced. From studies on primary flexor tendon repair it is known that the suture has to involve a certain amount of tendon fibres to gain strength; a 3 mm tendon grasp was considered ideal for the Kessler and cross-stitch repairs (Dona et al., 2004; Hatanaka and Manske, 1999). The step-cut can be considered as suturing two smaller tendons together with less tendon fibres to grasp. A previous study has reported that the strength is reduced when suturing a thin tendon to a thicker one compared with suturing two thick tendons (Fridén et al., 2015). This is in accordance with the findings from other techniques that link tendons of different size together (Mazurek et al., 2011). The present study supports that the thinner the tendon the less holding capacity of the suture.

The ultimate load of all three variations appears to be well above the strength needed for unrestricted active motion of the fingers (Savage, 1985. and 1988; Schuind et al., 1992). It has been found that the tendon repair must withstand at least 35 N for active tendon movement (Schuind et al., 1992). The half step-cut is the weakest tendon repair but is still almost five times as strong as reported by Schuind et al. (1992). Because of the low bulk it is ideal for secondary flexor tendon reconstruction when connecting the donor tendon with a tendon graft in the palm of the hand where space is restricted. It is possible that the strength of the side-to-side repair may partly be counteracted by increased resistance to motion, as it is the bulkiest of the repairs.

In secondary flexor digitorum profundus repair it is common to harvest a graft that is attached to the distal phalanx either by pullout suture, anchor, or the transverse intraosseous loop technique (TILT) (Tripathi et al., 2009). The strength of the three techniques in this study is higher by at least a magnitude of two compared with the ultimate load of these techniques (Brustein et al., 2001; McCallister et al., 2006; Tripathi et al., 2009). Stiffness and load at 5 mm elongation were not statistically different. At 10 mm elongation the side-to-side technique were statistically stronger than the half step-cut variation. It is above both the force needed for active unrestricted motion (Schuind et al., 1992). Even though the maximum load in the side-to-side group was the highest, the half step-cut has sufficient strength and stiffness to prevent elongation of the repair.

All repairs failed by the sutures shearing through the tendon longitudinally, showing that the suture material is not the limiting factor in the present study. Therefor changing to a stronger suture probably will not increase the strength. For the half step-cut 11 of the repairs failed by sutures pulling through on one side whilst losing the grip of the tendon on the other side (Figure 2).

The rationale for reducing the cross-sectional area of the repair is to lower the gliding resistance. The side-to-side repair and the step-cut have both been tested against the Pulvertaft but to our knowledge there are no studies testing different degrees of step-cut against the side-to-side repair. Side-to-side tendon suture for tendon transfers has been increasingly used recently and has similar strength to the Pulvertaft weave as has been shown in biomechanical studies. In a recent study on the Pulvertaft weave we found the maximum stiffness was reached after 13.5 mm elongation and the ultimate load after 23.7 mm (Strandenes et al., 2019). This is about twice the elongation compared with step-cut and side-to-side. The overall stiffness of the Pulvertaft construction was calculated to be 12.9 N/mm compared with 15.7 N/mm for the half step-cut.

The area was not doubled in the side-to-side repair. This is probably because the sutures squeeze the two tendons together. This finding was also observed for the one-third and half step-cut. Another reason may be that the area calculation is based on a true ellipse, an approximation that may not be accurate. When one tendon is half or less than the size of the diameter of the second tendon, we consider it safe to remove a part of the larger tendon that is equal to the cross-section area of the thinner tendon, thereby not increasing the cross-sectional area of the repair zone. In the clinical setting we have used this for reconstruction of the flexor pollicis longus when transferring the flexor digitorum superficialis tendon from the ring finger. Furthermore, to get a smoother transition and prevent gap formation between the tendons, a 6-0 monofilament, nonabsorbable suture is normally used in the clinical setting when making step-cut repairs. The aim of this is to reduce the friction by keeping the tendon ends flush with the tendon. This was not done in this in vitro study.

All of the repairs in this study are relatively stiff and reaches the maximum stiffness after a short elongation compared with the Pulvertaft technique. This makes it easier to find the right tension for the repair. It is important to stress that all of the repairs need to be sutured with the digit in slightly more flexion in tendon reconstruction, because there will be some elongation. In this study we found no difference in force until a 10 mm elongation was reached. At this elongation the side-to-side was stronger than the half step-cut repair. This is an elongation which most would recognize as a failure. At lower forces there were no differences in elongation. The step-cut technique occupies less space in the hand and with multiple transfers this can be important where the space is restricted.

Based on our findings we suggest that the half step-cut is safe to use at the proximal junction of the tendon graft to the tendon muscle complex in secondary flexor tendon reconstruction as well as in tendon transfers when starting early unrestricted active movement of the fingers and wrist.

FIGURE LEGENDS

Figure 1. The three tendons repair techniques. (A) Side-to-side. (B) One-third step-cut. (C) Half step-cut. The distance of overlap is 3.5 cm.

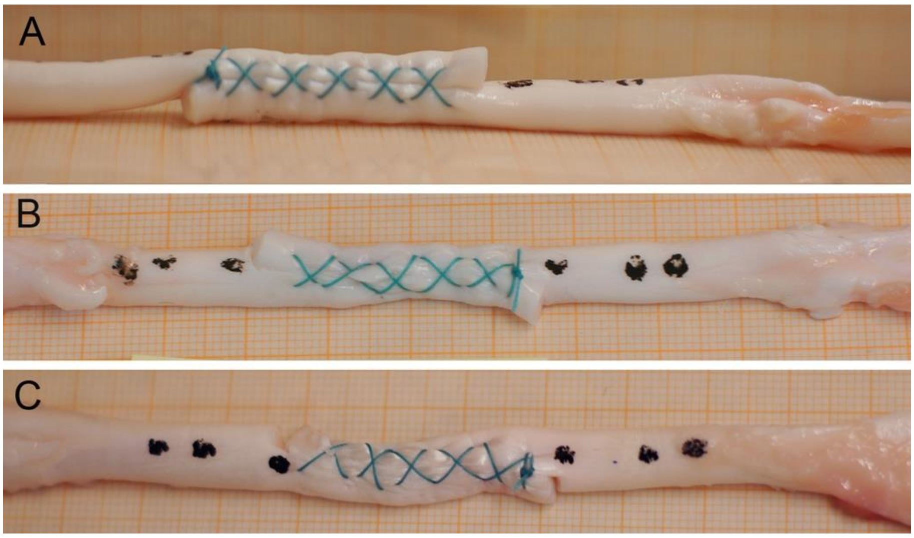

Figure 2. Failure mechanism after tensile testing. (A) Pull through of the sutures at both suture rows. (B) Sutures being pulled through only one side

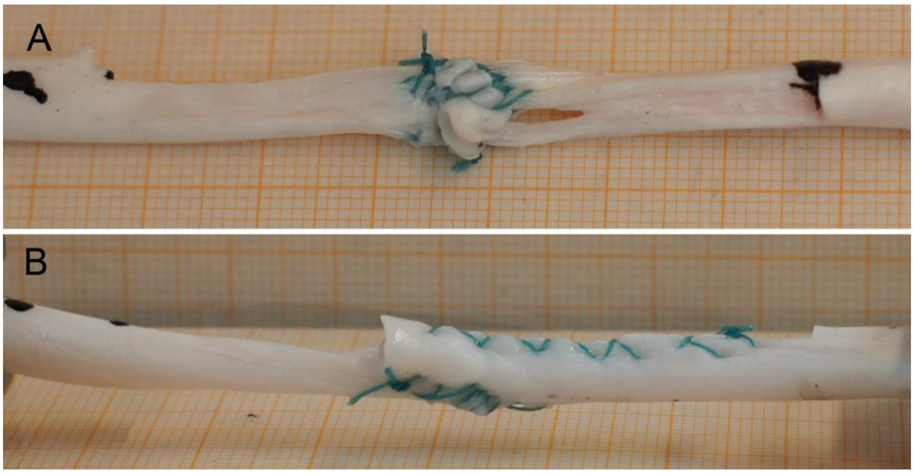

Figure 3. Maximum load (N) for each repair technique with mean (horizontal line) and standard deviation (whisker). **p*<0.05.

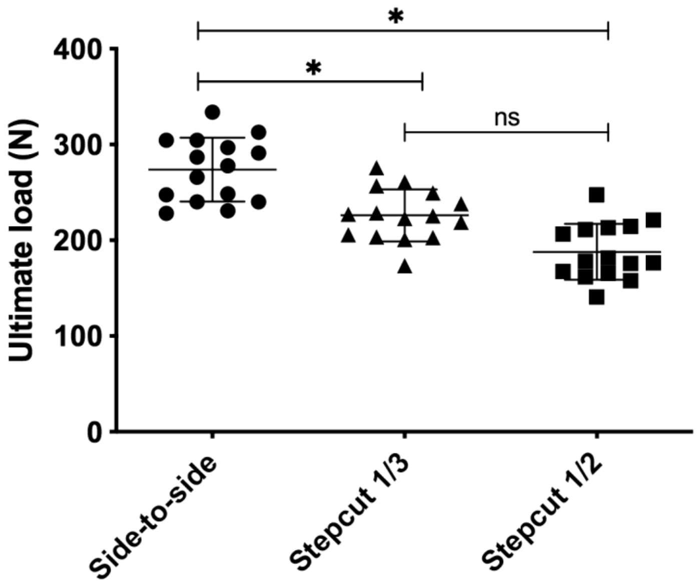

Table 1. Stiffness, load at max stiffness, load at 5- and 10 mm elongation and tendon dimensions in the three Side-to-side variations presented as mean values (standard deviation).

Side-to-side variations	Stiffness (N/mm)	Load at max stiffness (N)	Load at 5 mm elongation (N)	Load at 10 mm elongation (N)	Area outside overlap (mm^2)	Area overlap (mm^2)
Side-to-side (n=15)	30.2 (7.8)	105.8 (18.9)	70.2 (29.9)	189.9 (27.8)	39.0 (6.9)	55.0 (6.1)
One third step-cut (n=15)	27.8 (4.8)	100.8 (9.6)	79.9 (30.0)	187.5 (28.1)	38.9 (6.6)	43.4 (5.7)***
Half step-cut (n=15)	25.0 (3.3)	88.2 (9.7)*	72.9 (23.2)	165.1 (20.1)**	38.3 (6.2)	34.2 (4.4)***

*p=0.003, **p=0.03, ***p<0.0001. Statistically different compared with the Side-to-side repair.

REFERENCES

Becker H, Davidoff M. Eliminating the gap in flexor tendon surgery. A new method of suture. Hand. 1977, 9: 306-11.

Bidic SM, Varshney A, Ruff MD, Orenstein HH. Biomechanical comparison of lasso, pulvertaft weave, and side-by-side tendon repairs. Plast Reconstr Surg. 2009, 124: 567-71.

Brown SH, Hentzen ER, Kwan A, Ward SR, Fridén J, Lieber RL. Mechanical strength of the side-to-side versus Pulvertaft weave tendon repair. J Hand Surg Am. 2010, 35: 540-5.

Brustein M, Pellegrini J, Choueka J, Heminger H, Mass D. Bone suture anchors versus the pullout button for repair of distal profundus tendon injuries: A comparison of strength in human cadaveric hands. J Hand Surg Am. 2001, 26: 489-96.

Dona E, Gianoutsos MP, Walsh WR. Optimizing biomechanical performance of the 4-strand cruciate flexor tendon repair. J Hand Surg Am. 2004, 29: 571-80.

Fridén J, Tirrell TF, Bhola S, Lieber RL. The mechanical strength of side-to-side tendon repair with mismatched tendon size and shape. J Hand Surg Eur Vol. 2015, 40: 239-45.

Fuchs SP, Walbeehm ET, Hovius SE. Biomechanical evaluation of the pulvertaft versus the 'wrap around' tendon suture technique. J Hand Surg Eur Vol. 2011, 36: 461-6.

Gelberman RH, Amifl D, Gonsalves M, Woo S, Akeson WH. The influence of protected passive mobilization on the healing of flexor tendons: A biochemical and microangiographic study. Hand. 1981, 13: 120-8.

Gelberman RH, Vande Berg JS, Lundborg GN et al. Flexor tendon healing and restoration of the gliding surface. An ultrastructural study in dogs
e. J Bone Joint Surg Am. 1983, 65: 70-80.

Hashimoto T, Thoreson AR, An KN, Amadio PC, Zhao C. Comparison of step-cut and pulvertaft attachment for flexor tendon graft: A biomechanics evaluation in an in vitro canine model. J Hand Surg Eur Vol. 2012, 37: 848-54.

Hatanaka H, Manske PR. Effect of the cross-sectional area of locking loops in flexor tendon repair. J Hand Surg Am. 1999, 24: 751-60.

Hausmann JT, Vekszler G, Bijak M, Benesch T, Vécsei V, Gäbler C. Biomechanical comparison of modified Kessler and running suture repair in 3 different animal tendons and in human flexor tendons. J Hand Surg Eur Vol. 2009, 34: 93-101.

Havulinna J, Leppänen OV, Järvinen TL, Göransson H. Comparison of modified kessler tendon suture at different levels in the human flexor digitorum profundus tendon and porcine flexors and porcine extensors: An experimental biomechanical study. J Hand Surg Eur Vol. 2011, 36: 670-6.

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? J Hand Surg Eur Vol. 2011, 36: 663-9.

Mazurek T, Strankowski M, Ceynowa M, Roclawski M. Tensile strength of a weave tendon suture using tendons of different sizes. Clin Biomech. (Bristol, Avon) 2011, 26: 415-8.

McCallister WV, Ambrose HC, Katolik LI, Trumble TE. Comparison of pullout button versus suture anchor for zone i flexor tendon repair. J Hand Surg Am. 2006, 31: 246-51.

Pulvertaft RG. Tendon grafts for flexor tendon injuries in the fingers and thumb; a study of technique and results. J Bone Joint Surg Br. 1956, 38-b: 175-94.

Rivlin M, Eberlin KR, Kachooei AR et al. Side-to-side versus pulvertaft extensor tenorrhaphy-a biomechanical study. J Hand Surg Am. 2016, 41: e393-e7.

Savage R. In vitro studies of a new method of flexor tendon repair. J Hand Surg Br. 1985, 10: 135-41.

Savage R. The influence of wrist position on the minimum force required for active movement of the interphalangeal joints. J Hand Surg Br. 1988, 13: 262-8.

Schuind F, Garcia-Elias M, Cooney WP, 3rd, An KN. Flexor tendon forces: In vivo measurements. J Hand Surg Am. 1992, 17: 291-8.

Shi D, Wang D, Wang C, Liu A. A novel, inexpensive and easy to use tendon clamp for in vitro biomechanical testing. Med Eng Phys. 2012, 34: 516-20.

Strandenes E, Ellison P, Mølster A, Gjerdet NR, Moldestad IO, Høl PJ. Strength of pulvertaft modifications: Tensile testing of porcine flexor tendons. J Hand Surg Eur Vol. 2019, 44: 795-9.

Tripathi AK, Mee SN, Martin DL, Katsarma E. The "Transverse intraosseous loop technique" (TILT) to re-insert flexor tendons in zone 1. J Hand Surg Eur Vol. 2009, 34: 85-9.