Strength of Pulvertaft modifications

Tensile 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, University of Bergen, Norway

5. Department of Clinical 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: Pulvertaft weave; tendon transfer; biomechanics; tendons; tensile strength

Acknowledgements:

The authors wish to thank Gøril Skaale Johansen, The Department of Photo & Illustration, UiB for the illustrations of the tendon techniques.

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.

Strength of Pulvertaft modifications

Tensile testing of porcine flexor tendons

ABSTRACT

The aim of the study was to present two new modifications of the Pulvertaft weave allowing higher number of weaves without need of a longer overlap. The mechanical properties were evaluated and compared with the traditional technique. 45 pairs of porcine flexor tendons were randomised to Pulvertaft with three weaves, double Pulvertaft and locking Pulvertaft. In the last two one of the tendons in each repair was split in two before weaving. The two new variations had higher ultimate tensile strenght than the traditional Pulvertaft weave. Analyses of the stiffness showed no differences between the three groups. All repairs failed by the sutures being sheared through the tendons splitting the tendon fibers longitudinally. The two modifications were both stronger than the Pulvertaft weave and comprises an alternative when a strong connection is needed and a longer overlap is impossible.

Level of evidence: In vitro study

INTRODUCTION

Tendon transfer after nerve damage or old tendon injuries requires early range of movements to gain an optimal result. A strong joint between the tendon connected to the muscle and the recipient tendon will allow active movement immediately after the operation.

Pulvertaft weave was first described by R. Guy Pulvertaft in 1956 (Pulvertaft, 1956) as a method to join tendons of different diameter. It is one of the most common methods used in tendon transfer or tendon reconstruction being simple to perform and well proven. Nevertheless, there are many variations. In the original paper (Pulvertaft, 1956) there is no description of the number of interlacing tendon weaves. The illustrations show a total of six stiches, but it is not obvious if there are cross- stitches or how the stitches and interlaces were spatially arranged. Prior studies on the technique describe weaves in different planes but the way they are sutured together and the number of weaves varies (Bidic et al., 2009; De Smet et al., 2008; Fuchs et al., 2011; Jeon et al., 2009; Kulikov et al., 2007).

It has previously been shown that cross stitching is stronger than the horizontal mattress suture, and that up to four weaves creates higher strength (Gabuzda et al., 1994), but still it was recommended to make as many weaves as possible. However, in many clinical situations it can be difficult to obtain sufficient tendon length to accommodate more than three weaves.

Strength of Pulvertaft modification. The Journal of Hand Surgery (Eur)

The aim of this study was to present and to biomechanically evaluate two new modifications of the Pulvertaft weave by making two weaves parallel to keep the overlap short.

METHODS

Material

Flexor digitorum profundus tendons from 45 pigs were used in the experiment. The tendons were obtained from one-year old pigs at a local butchery. No ethical approvals were needed. Only the tendons from the two central rays of the forelimbs were selected. In total 90 tendons were used to create 45 repairs. The specimens 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.

Suture techniques

The tendons were randomly allocated in three groups (n=15 pairs in each group) (Figure 1):

A) Pulvertaft (PT); one the tendons was woven through three incisions in the recipient tendon, two horizontal and one vertical incision (Figure 1A).

B) Double Pulvertaft (DP); Pulvertaft modified by two parallel rows containing three incisions each are made in one of the tendons. In the second tendon a longitudinal split is made creating two arms. One arm is then woven through each row of slits in opposing directions. At each weave and at the ends they are sutured in the same manner as in Pulvertaft Weave (Figure 1B).

C) Locking double Pulvertaft (LPT). In the recipient tendon three incisions were made in the horizontal plane but at different offsets. The other tendon was split in the same manner in the DP group and woven through the slits. The second tendon was pulled through the same slit and then through the first arm. This process was repeated for each of the two last incisions that locked the tendons together (Figure 1C).

In all groups the three weave points were secured with cross-stitches using 3-0 polyester suture (Ethibond Excel, Ethicon, Johnson & Johnson, Somerville, NJ, USA). Each end of the tendons was anchored with a mattress suture. The total distance of overlap was intended to be 3.5 cm. During the suturing and until the mounting of the repairs the tendons were kept moist with saline at room temperature (21-23°C).

Measurement of cross-sectional dimensions

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

Tensile testing

Tensile properties of the constructs were measured in a tensile testing machine (Instron 5966, Instron Corp, Canton, MA, USA) with a custom made grips (Shi et al., 2012). During testing the specimen were recorded with a video camera being part of the testing system (Instron advanced video recorder, Instron Corp, Canton, MA, USA) which also recorded strain. In addition, a standard video camera (Sony α55, Tokyo, Japan) recorded at another angle in order to obtain detailed information about the failure mechanism.

The preload was set to 2.0 N and the distance between the grips was 6.5 cm. Crosshead speed was 25 mm/minute and continued until final failure. From the resulting load-extension data maximum load, load at 10 mm elongation and maximum stiffness was calculated.

In this study we defined failure as the point where the load curve dropped after reaching the maximum load.

Statistical methods

Power analysis based on pilot experiments indicated that 15 parallels of each experiment was needed ($\beta=0.8$). Arithmetic mean and standard deviation were calculated. Repeated-measures ANOVA and post hoc multiple comparison with Tukey correction were used to evaluate differences in ultimate strength and tendon dimension among the three Pulvertaft variations. Linear regression analysis was used to assess the association between tendon size, maximum load, stiffness, and load at 10 mm elongation. $p < 0.05$ was considered to be statistically significant.

RESULTS

The cross-section area of all of the tendons was not statistically different, neither outside the overlap ($p=0.095$) nor at the suturing overlap ($p=0.34$) (Table 1). The ultimate tensile strength was statistically different between groups (ANOVA, $p < 0.001$) (Figure 2 a, b, c; Table 1). Post hoc testing identified that Locking Pulvertaft was stronger than the Pulvertaft weave ($p<0.001$), as were Double Pulvertaft ($p=0.001$). The Locking Pulvertaft was not statistically stronger than the Double Pulvertaft (p=0.304). The load at 10 mm elongation was not different between the three groups (p=0.652). A difference in the maximum stiffness was observed between the three groups (p=0.024). Post hoc testing identified that the Double Pulvertaft was statistically stiffer than Pulvertaft weave (p = 0.024), but not Locking Pulvertaft (p = 0.797).

Linear regression analysis did not show any effect of tendon size (cross-sectional diameter) on maximal load, stiffness or load at 10 mm elongation for any of the Pulvertaft techniques.

The specimens failed after reaching the maximal load by the sutures being sheared through the tendons, splitting the tendon fibres longitudinally. There was no suture rupture or knot unravelling.

DISCUSSION

Early active motion to prevent tissue adhesions is important as part of a postoperative protocol that is easily managed by the patient. Thus strong tendon-to-tendon interfaces are required. Stronger interfaces can be achieved by increasing the number of weaves but then longer overlap is required, which is not always practically achievable.

In the present study we found that tensile strength in Double Pulvertaft and Locking Pulvertaft was approximately 20% higher than the Pulvertaft repair. This demonstrates that increasing the number of weaves by splitting one of the tendons increases strength. This has the advantage that higher strength is obtained without the need of a longer overlap to accommodate more weaves as with the original PT weave. This can be of importance when there is need of tendon transfer that could be subjected to high loads, as in the lower extremities. The tendons are also exposed to passive strain and unintentional loads by accidents like falling. Less compliant patients can also benefit from a stronger tendon transfer.

The tensile strength of all three Pulvertaft techniques was higher than those reported in an earlier investigation (Gabuzda et al., 1994). This could be due to different dimensions and tendon origin. In our study, the number of stitches were kept constant, to avoid a confounding effect. More than four stiches do not necessarily increase the strength (Fuchs et al., 2011; Gabuzda et al., 1994). Also, cross-stitches are stronger than mattress sutures (Fuchs et al., 2011; Gabuzda et al., 1994), as used in many studies comparing new Pulvertaft techniques.

It has been stated that the maximum contractile force of the Biceps Brachii is 250 N (Friden et al., 2015) and that no muscle in the forearm can develop higher max force than 100N. Moreover, it has been suggested that there is a reduction in strength during the first week after flexor tendon surgery (Urbaniak, 1975) although this reduction has been questioned (Boyer et al., 2001). Anyhow, the strongest repair should be made without excessive shortening or increased bulkiness.

The variation of strength within each group probably reflects that it is difficult to perform the repair in exactly the same manner each time. Especially with the two Pulvertaft variations it can be difficult to obtain a good grip of all three tendon ends with the needle each time.

The two new variations of Pulvertaft weave tested in the present study have a higher tensile stiffness than the three-weave Pulvertaft. The reason could be due to the direction of the weave. The weaves in both Double Pulvertaft and Locking Pulvertaft are in one plane. In contrast, the Pulvertaft weave has weaves in the transverse direction since the incisions are oriented 90° to each other in the longitudinal plane.

It is a goal in tendon repair to keep the cross-sectional area as close to the rest of the tendon as possible in order to reduce the friction during tendon gliding. The present study showed that the cross-section at the overlapping region was not statistically different between the three groups.

The finding that suture rupture or knot unravelling did not occur but that the sutures were sheared through the tendons, indicating that the tendon tissue is the limiting factor, not the suture properties. This is in contrast to other studies on Pulvertaft weaves (Bidic et al., 2009; Brown et al., 2010) and could be explained by the lower local stress with cross stiches and superior anchoring of the tendons. Furthermore, the two stitches were tied at each end first to obtain even tension between the cross-stiches in the middle to prevent one stitch to take all load.

There are some limitations of this study; one is the use of non-human tendons. Pig tendons have been shown to have similar biomechanical properties as human tendons and are commonly used in biomechanical testing (Hausmann et al., 2009; Havulinna et al., 2011; Mao et al., 2011; Smith et al., 2005). The testing is quasi-static, and cyclic loading could have simulated the in vivo situation more closely.

For all Pulvertaft techniques it can be difficult to obtain the same tension between the stitches when suturing the tendons together. In the clinical situation, this might be easier to achieve by starting with the two stiches at each end of the weave and then do a tenodese test to get a more uniform tension between all stitches at each end of the repair. This is important since the ultimate strength of the repair is dependent on even stress distribution on the stitches. If one stich is holding most of the load the repair will probably fail prematurely because of overstressing. This could occur in all three techniques since they rely on single stitches and not continuous sutures. It has been questioned if cross-stitches will interfere with the blood supply to the tendon (Tanaka et al., 2006) but appears not to be a major issue in the clinical setting.

In clinical practice a reliable, strong and simple technique is required. Pulvertaft has proven to be so. By using cross-stitches and increasing the weaves, as with the Double Pulvertaft or Locking Pulvertaft, it is possible to increase the maximum strength without the need of a long or bulky overlap. Where possible, these techniques could be used with more weaves to increase strength of the construct. Previous studies on side-to-side techniques have revealed mean ultimate loads ranging from 89 N to 338 N (Bidic et al., 2009; Brown et al., 2010; Friden et al., 2015; Rivlin et al., 2016) but we obtained somewhat higher values. The stiffness values were similar to our findings in the Friden et al. study (Friden et al., 2015). The two new variations are prone to elongate to some extent as with the well-proven Pulvertaft. Thus, it is important to apply pre-tension.

Conclusion: Based on this in vitro experiment it is indicated that the two new techniques are favourable when a strong link is required without enough tendon overlap to perform a Pulvertaft weave with more than four interlaces.

Strength of Pulvertaft modification. The Journal of Hand Surgery (Eur)

FIGURE LEGENDS

Figure 1: Illustration showing the three tendons techniques; A: Pulvertaft weave, B: Double Pulvertaft, C: Locking Pulvertaft. The total distance of overlap was 3.5 cm.

Figure 2: Load (N) - extension (mm) curves for all the experiments and each of the Pulvertaft techniques tested. A: Pulvertaft weave, B: Double Pulvertaft, C: Locking Pulvertaft.

LIST OF REFERENCES

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.

Boyer MI, Gelberman RH, Burns ME, Dinopoulos H, Hofem R, Silva MJ. Intrasynovial flexor tendon repair. An experimental study comparing low and high levels of in vivo force during rehabilitation in canines. J Bone Joint Surg Am. 2001, 83-A: 891-9.

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: 540-5.

De Smet L, Schollen W, Degreef I. In vitro biomechanical study to compare the double-loop technique with the pulvertaft weave for tendon anastomosis. Scand J Plast Reconstr Surg Hand Surg. 2008, 42: 305-7.

Friden 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.

Gabuzda GM, Lovallo JL, Nowak MD. Tensile strength of the end-weave flexor tendon repair. An in vitro biomechanical study. J Hand Surg Br. 1994, 19: 397-400.

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

Havulinna J, Leppanen OV, Jarvinen TL, Goransson 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.

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. J Hand Surg Am. 2009, 34: 1074-9.

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. J Hand Surg Eur Vol. 2007, 32: 377-81.

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.

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.

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.

Smith AM, Forder JA, Annapureddy SR, Reddy KS, Amis AA. The porcine forelimb as a model for human flexor tendon surgery. J Hand Surg Br. 2005, 30: 307-9.

Tanaka T, Zhao C, Ettema AM, Zobitz ME, An KN, Amadio PC. Tensile strength of a new suture for fixation of tendon grafts when using a weave technique. J Hand Surg Am. 2006, 31: 982-6.

Strength of Pulvertaft modification. The Journal of Hand Surgery (Eur)

Urbaniak JR. Tendon suturing methods: Analysis of tensile strengths. In: A.A.O.S (Ed.) *Symposium on tendon surgery in the hand*, A.A.O.S, 1975.

Table 1

Table 1: Ultimate load, stiffness, load at 10 mm elongation and tendon dimension among the three Pulvertaft variations presented as mean values (standard deviation).

Pulvertaft variations	**Ultimate Load (N)**	**Stiffness (N/mm)**	**Load at 10 mm elongation (N)**	**Area outside overlap (mm^2)**	**Area overlap (mm^2)**
Pulvertaft weave	308.5 (44.0)	28.7 (5.3)	129.6 (28.8)	40.3 (5.6)	77.6 (11.5)
Double Pulvertaft	381.9* (61.4)	35.3 (7.8)*	142.4 (41.6)	40.9 (5.3)	81.1 (10.0)
Locking Pulvertaft	409.8* (45.9)	33.7 (6.6)*	143.9 (62.2)	36.8 (5.4)	75.9 (7.1)

*Statistically different compared with the Pulvertaft weave.

Figure 1 a-c

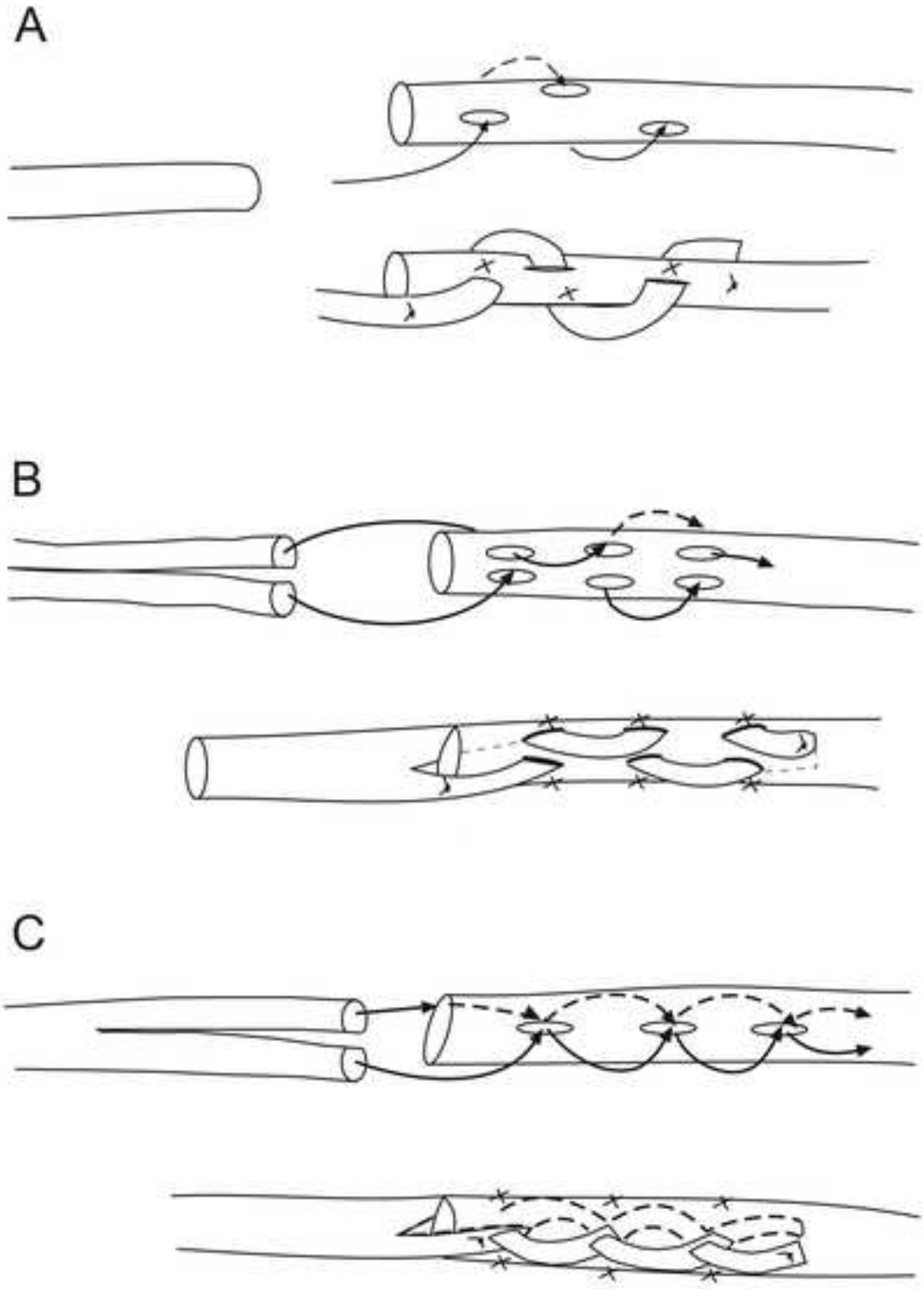
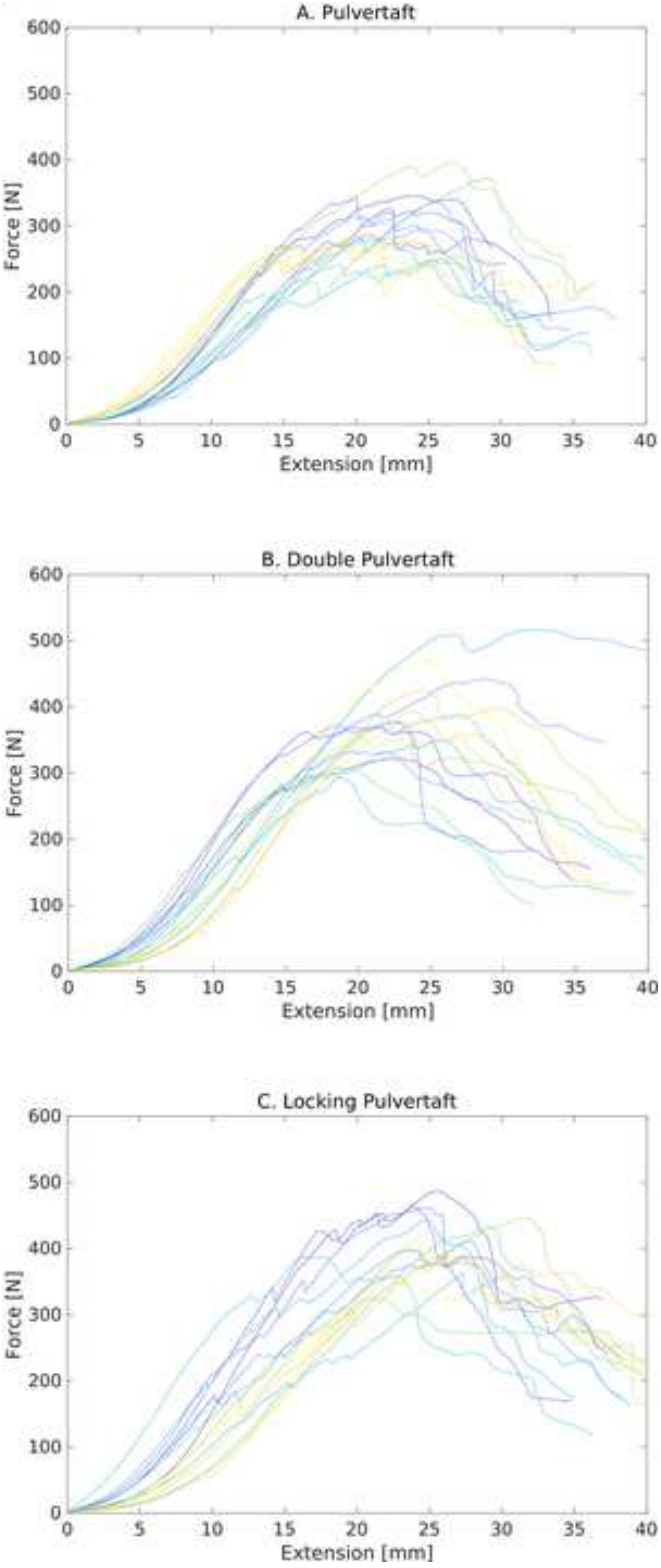


Figure 2 a-c


A. Pulvertaft
Force [N]
Extension [mm]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
B. Double Pulvertaft
Force [N]
Extension [mm]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
C. Locking Pulvertaft
Force [N]
Extension [mm]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40