Positioning of the cross-stitch on the Modified Kessler core tendon suture

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ABSTRACT

Cryopreserved human tendons were sutured with different variations of a modified Kessler-type grasping suture in a series of different designs in order to assess the influence of the distance between the cross-stitch on the core suture (5 and 10 mm from the cut tendon edge) on the peripheral suture. An original mathematical model was employed to explain the mechanical behaviour (strength, deformation, and distribution of load) of the different suture designs. The effect of the peripheral epitendinous suture, combined with the distance of the core suture, was evaluated.

The variation of core suture distance had no relevant consequences on the overall resilience of the design. However, increasing the distance between the cross-stitches of the core suture reduces the deformation that is absorbed not only by the core suture itself but also by the peripheral suture.

Adding a peripheral epitendinous suture to a 10-mm design almost doubles the breaking load in absolute values. The mathematical model predicts that the peripheral suture will support a greater load when the distance of the core suture cross-stitches is increased. The evidence level is II.

Keywords: Biomechanics; flexor tendon; repair; core and peripheral suture; resistance.

INTRODUCTION

Outcomes after repairs of finger flexor tendons have certainly been improved by early motion programs (Ketchum et al., 1977; Silfverskiöld and Anderson, 1993; Wade et al., 1989). Obtaining optimal tendon excursion reduces the risk of adhesions or minimizes their effect and makes them compatible with normal finger functions (Trail et al., 1989; Trail et al., 1992). However, early motion requires a design capable of resisting the forces applied without altering normal tendon healing biology. This involves a combination of high initial resistance (Ketchum et al., 1977; Mason and Allen, 1941; Wade et al., 1989) (avoiding the occurrence of gapping and snagging) with the minimum of tissue strangulation, which impedes intrinsic vascularization and thus healing potential (Mason and Allen, 1941).

In the last years, several studies have been carried out about the materials and technique of tie (Gil et al., 2012; Ortillés et al., 2014, von Trotha et al., 2017). The Kessler type suture (Gil Santos, 1993; Kessler, 1973; Moriya et al., 2010) and its modifications have been the most frequently used in repairing flexor tendons in the hand. However, in our opinion, even though this type of suture is today widely employed, this design lacks systemization in several important aspects, such as in the distance of the cross-stitch from the cut tendon edge. The aim of this study was to apply an original mathematical model in order to assess the mechanical behavior of the Modified Kessler grasping tendon suture when the cross-stitch is placed at various distances from the edge and to quantify the influence of this distance on the peripheral epitendinous suture (also refered as “peripheral” or “epitendinous”).

MATERIALS AND METHODS

In the study 20 flexor tendons obtained from 10 human cadavers involved in violent deaths (10 in traffic accidents and one had been stabbed to death) with no history of organic pathology were used. The tendons were frozen by the Arnoczky method (Arnoczky et al.,

1986) and after thawing in a saline ClNa 9‰ bath for 3 hours at a constant temperature of 36º in a thermostatically controlled Kowell® oven; tenorrhaphy was carried out on the different series for a total of 30 tests.

Tenorrhaphy. Experimental Model

The tendon sutures were prepared by immersing specimens in a physiological solution under optical magnification by means of a Zeiss® OPMI-1 surgical microscope and Keeler® type 2.5 x 300 magnifiers, using a millimeter grid on the bottom of the recipient as a guide to place the sutures in the required position.

All the core sutures had six simple knots, tied alternately towards right and left, with propylene monofilament non resorbable thread 4-0 sutures. The peripheral suture was also made with propylene monofilament non resorbable 6-0 single-stranded running epitendinous. Five different series of samples were tested (Fig.1): a) intact tendons; b) Kessler at 5 mm from the cut edge; c) Kessler at 10 mm; d) Kessler at 5 mm plus epitendinous suture at 2 mm; e) Kessler at 10 mm plus epitendinous at 2 mm.

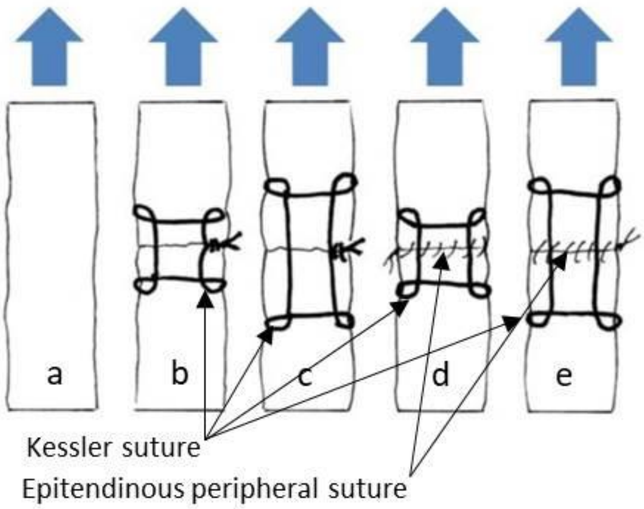

Fig. 1.- The five series tested (left to right): a) intact tendons; b) Kessler at 5 mm; c) Kessler at 10 mm; d) Kessler at 5 mm plus epitendinous suture; e) Kessler at 10 mm plus epitendinous.

Tendon Preconditioning and Biomechanical Study

Samples were tested on an Adamel Lhomargy DY-34® device (Adamel Lhomargy S.A., France) (Fig.2). A stress-strain test was carried out by applying a constant strain rate until the suture material reached breaking point, while measuring the load throughout the test.

Fig. 2.- DY.34 (Adamel Lhomargy S.A.) mechanical testing machine.

Preconditioning is considered necessary in *in vitro* experiments before accepting the registered values (Hooley, 1977; Monleón and Díaz, 1990). It simply consists of a preliminary loading and unloading of the specimen, in such way that after this loading and unloading, the results can be considered as repetitive (Fig.3).

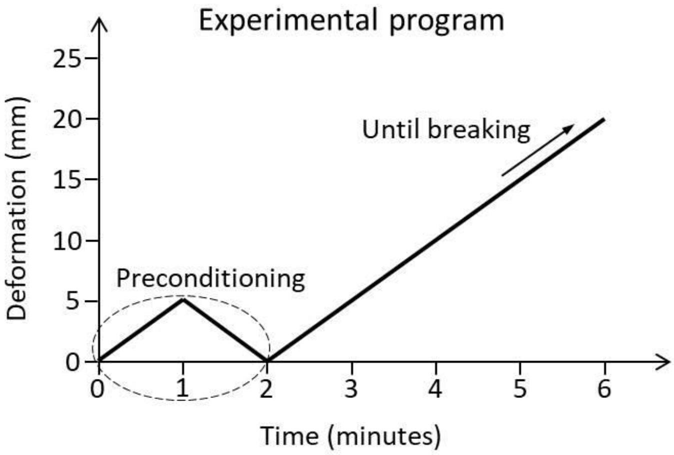

Fig. 3.- Experimental program.

The experimental loading program itself consisted of two consecutive stretching cycles divided into three stages: *1st stage*, stretching at 5 mm/min to an absolute value of 5mm; *2nd stage*, the tendon was allowed to return to its original position (null force) at a rate of 5 mm/min; 3rd stage, stretching at 5 mm/min until breakage of sutured specimens. This program was used in all the tests, the unsutured tendons being stretched between clamps. The device's associated software converts the experimentally measured load and displacement magnitudes into the values that appear on the graphs.

Mathematical Model

A mechanical model is proposed in order to understand the experimental results. This model divides the sutured tendons into three mechanically different parts, consisting of: the tendon, the Kessler core suture, and the epitendinous peripheral suture. Each of these parts was characterized by essays on different samples, as indicated above.

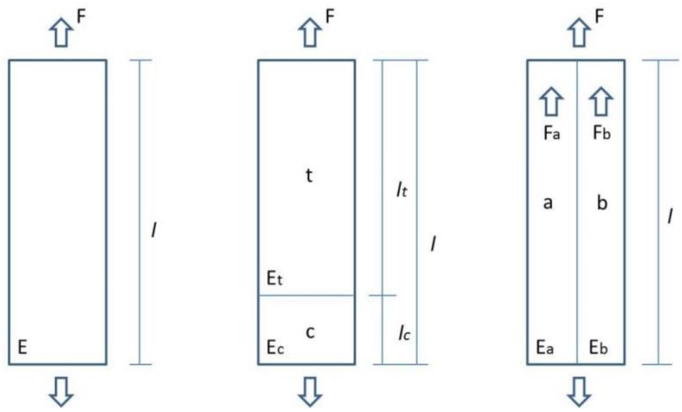

Fig. 4.- Mechanical model: a) single element; b) tendon plus core suture associated in series; c) two elements associated in parallel.

In the stretching device, a force F and displacement Δl are measured (Fig. 4a). If l_O is the initial length of the sample, $\varepsilon = \dfrac{\Delta l}{l_0}$ denotes the strain of the specimen. E is the ratio between load and strain, which we call "stretching modulus": $E = \dfrac{F}{\varepsilon}$. As the stretching modulus can only be assumed to be approximately constant in the linear zone (in the non-linear zone it varies), only in this behavioral zone can a numerical comparison be carried out between intact and sutured tendons.

This definition of stretching modulus is not frequently used in material science. Instead stretching modulus is usually stated ~~as~~ the ratio between stress, $\sigma = \frac{F}{A}$ (A being the cross-section of the specimen), and strain, $\frac{\sigma}{\varepsilon}$. This magnitude is not significant for our purposes, since our specimens ~~has~~ have a badly-defined cross-sectional area, due both to the lack of uniformity of the tendinous bundles and, more importantly, to the fact that the effectively loaded section of the sutured tendons was not that of the tendon itself but that of the suture strands. Therefore, these issues justifie our definition of E.

In order to understand the deformation mechanisms in the specimens we can modelize the experimental behaviour as follows:

a) Intact Tendons

Intact tendons (no sutures) were tested in accordance with the scheme shown in Figure 4a. The stretching modulus of tendon E_t was taken as the average value of the linear stretching modulus in the linear tendon deformation zone during the 2nd loading stage of every experimental measurement.

b) Tendons with core sutures only (no epitendinous peripheral suture)

The specimen model is now heterogeneous and consists of two elements in series representing, respectively, the tendon and the Kessker core suture loop as it is actually configured (i.e. its effectiveness from a mechanical standpoint (Fig.4b)). These elements are individually characterized by the corresponding stretching moduli E_t and E_c, while the specimen as a whole is characterized by an apparent strectching modulus, E_{ap}, as used in the experiments. The taken value for E_t is that of intact tendons; E_c is given by the computed value from the tests on tendons with core sutures. Since two different core sutures were performed (at 5 and 10 mm), the value of E_c is obtained for each one. In order to calculate these values we must on first establish the mechanical model of two elements in series, as can be seen in Figure 4b.

The initial length of the element representing the tendon is called l_t^0; the inital length of the core suture element is l_c^0; and $l^0 = l_t^0 + l_c^0$ is the initial length of the specimen model. As both of them are associated in series, the load withstood by the specimen is the same as that withstood by the tendon element and the core suture element: $F = F_t = F_c$

If $\Delta l, \Delta l_t$ and Δl_c are respectively the deformation of the specimen, tendon element and core suture element, $\varepsilon, \varepsilon_t$ and ε_c the corresponding strains, $E_{ap,} E_t$ and E_c their stretching moduli, $k_c^0 = \frac{l_c^0}{l^0}$ and $k_t^0 = \frac{l_t^0}{l^0}$ the ratios of initial length, and $\alpha_t = \frac{\Delta l_t}{\Delta l}$ and $\alpha_c = \frac{\Delta l_c}{\Delta l}$ the corresponding strain ratios of the tendon and core suture elements, then:

$$\frac{1}{E_{ap}} = \frac{k_c^0}{E_c} + \frac{k_t^0}{E_t} \quad [1] \qquad E_{ap} = \alpha_t E_t + \alpha_c E_c \quad [2] \qquad \alpha_c + \alpha_t = 1 \quad [3]$$

c) Tendons with core and peripheral sutures

Again an heterogeneous model specimen is considered, this time with three elements: core suture, epitendinous suture and tendon. The core and epitendinous sutures work together and share the load. As these sutures have different lengths, a small part of the tendon will be associated in series with the epitendinous suture, and this set will be in parallel with the core suture. Everything associated in series with the tendon element. Each of these sets is individually characterized by its stretching modulus, as can be seen in Figure 5.

For E_t and E_c we take the values expressed above as calculated in previous assays. E_p is calculated from the results of the tests on samples with both sutures, applying the equations corresponding to the model in Figure 5.

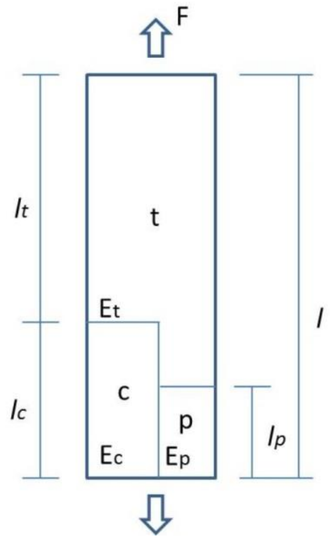

Fig. 5.- Model of tendon with core suture plus epitendinous peripheral.

However, in order to find the equations leading to this model we must on first set up the equations of two elements in parallel (Fig.4c):

Both elements are now of the same length $l = l_a = l_b$. As the force applied is shared between both blocks: $F = F_a + F_b$

The apparent stretching modulus of the specimen made up by two elements in parallel (Fig.4c) is:

$$E_{ap} = \frac{F}{\frac{\Delta l}{l^0}} = \frac{F_a + F_b}{\frac{\Delta l}{l^0}} = E_a + E_b \qquad [4]$$

Once the relationship between the stretching moduli of an association in parallel is known we can write the equations of the model in Figure 5, bearing in mind that the initial length of the epitendinous suture l_p^0 is associated in series with a length of the tendon element with an initial value of $l_c^0 - l_p^0$. This association in series is at once in parallel with the core suture element, with an initial length l_c^0 and this association is in series with the rest of the tendon element. By expressing the equations of these associations in the same way as the previous ones ($k_c^0 = \frac{l_c^0}{l^0}$, $k_t^0 = \frac{l_t^0}{l^0}$, $k_{pc}^0 = \frac{l_p^0}{l_c^0}$, $\alpha_c = \frac{\Delta l_c}{\Delta l}$, $\alpha_t = \frac{\Delta l_t}{\Delta l}$ and $\alpha_p = \frac{\Delta l_p}{\Delta l}$), it comes:

$$\frac{1}{E_{ap}} = \frac{k_t^0}{E_t} + \frac{k_c^0}{E_c + \frac{1}{\frac{k_{pc}^0}{E_p} + \frac{1-k_{pc}^0}{E_t}}} \qquad [5]$$

$$E_{ap} = \alpha_t E_t + \alpha_c E_c + \frac{\alpha_p E_p}{k_{pc}^0} \qquad [6]$$

$$\alpha_c + \alpha_t = 1 \qquad [7]$$

$$\alpha_t + \frac{E_p}{E_t}\left(\frac{1}{k_{pc}^0} - 1\right)\alpha_p + \alpha_p = 1 \qquad [8]$$

$$\frac{F_c}{F_t} = \frac{1}{1 + F_p / F_c} \qquad [9]$$

$$\frac{F_p}{F_t} = \frac{1}{1 + F_c / F_p} \qquad [10]$$

Statistical analysis

The statistics were calculated assuming parametric data of a normally distributed population and considering multiple comparisons among the preestablished series using the student t-test. The criterion for significant difference was a value of $P< 0.05$.

RESULTS

Experimental results. Applying the model.

a) Intact tendons. Series 1.

In this series the mean value of the linear stretching modulus was $\mathrm{E_t} = 5000 \ \mathrm{SD} \ 2000 \ \mathrm{N}$, which was taken as the value of the tendon element in the subsequent model applications.

b) Tendons with core suture. Series 2 and 3.

Two types of core suture were tested: those with a cross-stitch at a distance of 5 mm (Series 2) and 10 mm from the tendon edge (Series 3). The mean value of the stretching modulus of the tested specimens was taken as the apparent stretching modulus of each series.

The initial length of the core suture element of the cross-stitch in each case was taken equal to the position from the tendon edge, $l_c^0 = 5\ mm$ and $l_c^0 = 10\ mm$. By applying Eq.[1] the linear modulus of each core suture were obtained. Applying Eq.[2] and Eq.[3] we calculated α_t and α_c for the tendon and core suture elements, obtaining the results shown in Table I.

	Series 2 5 mm Cross-Stitch	Series 3 10 mm Cross-Stitch
E_{ap} (N)	370 (SD 110)	350 (SD 210)
E_c (N)	14 (SD 3)	23 (SD 8)
α_c	0.93	0.96
α_t	0.07	0.04

Table I: Results of measurements and applying the model to Series 2 and 3.

c) Tendons with core suture plus a peripheral epitendinous. Series 4 and 5

The initial length of the epitendinous suture element was taken $l_p^0 = 2\ mm$. As on the preceding case, two different core sutures were made with $l_c^0 = 5\ mm$ and $l_c^0 = 10\ mm$. The apparent stretching modulus of each tested serie tested was taken the mean value of the serie. The stretching modulus of the epitendinous suture in each serie was calculated from these values plus those of the previously calculated stretching moduli of the tendon and core suture elements, applying Eq. [5]. However, since the epitendinous suture was included in both series, the mean value of all the specimens tested in Series 4 and 5 was taken as the value of the linear stretching modulus of this suture, $\overline{E}_p$. α_t, α_c and α_p were computed from the stretching modulus thus obtained applying Eqs.[6] [7] and [8]. Finally, from Eqs.[9] and [10] we calculated the force on the core and epitendinous sutures related to the total force applied to the suture in each series. The results are given in Table II.

	Series 4 5 mm Cross-Stitch	Series 5 10 mm Cross-Stitch
E_{ap} (N)	440 (SD 120)	680 (SD 230)
E_p (N)	7	16
$\overline{E}_p$ (N)	14	
α_c	0.92	0.88
α_p	0.92	0.87
α_t	0.08	0.12
F_c/F_t	0.29	0.24
F_p/F_t	0.71	0.76

Table II: Results of measurements and applying the model to Series 4 and 5.

Macroscopic Findings. During the preliminary stretching tests, carried out as part of the system setup, was noticed that the longitudinal stitches tended to occupy the tendon central zone (due to the axialization phenomenon). It was also noticed the rotation of the tendon near the cut edge if the suture had not been properly placed (longitudinal stitches in the same frontal plane and equidistant from the sagittal tendinous plane) (Fig.6).

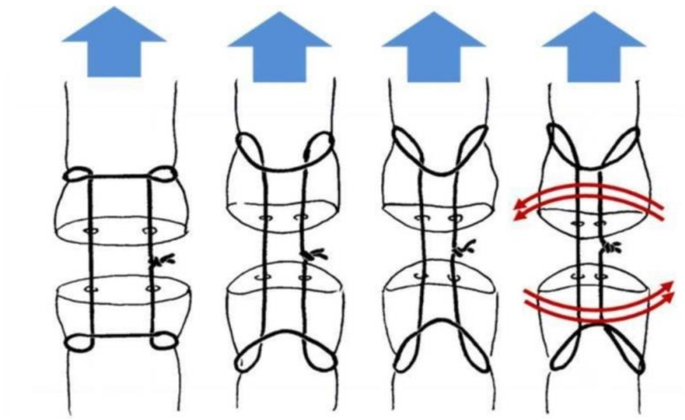

Fig. 6.- Phenomenon of axialization and rotation of the tendon near the cut edge

The core suture did not come untied in any of the tests, as breakage always happened on first at different points of the design for the 5 mm and 10 mm sutures. In all the tests breakage occurred in the longitudinal stitch, close to the knot in the 10 mm cross-stitch suture specimens, and near to the longitudinal-transversal loop in the 5 mm cross-stitch specimens (Fig.7). After the breakage of the longitudinal stitch, the knot disappeared inside

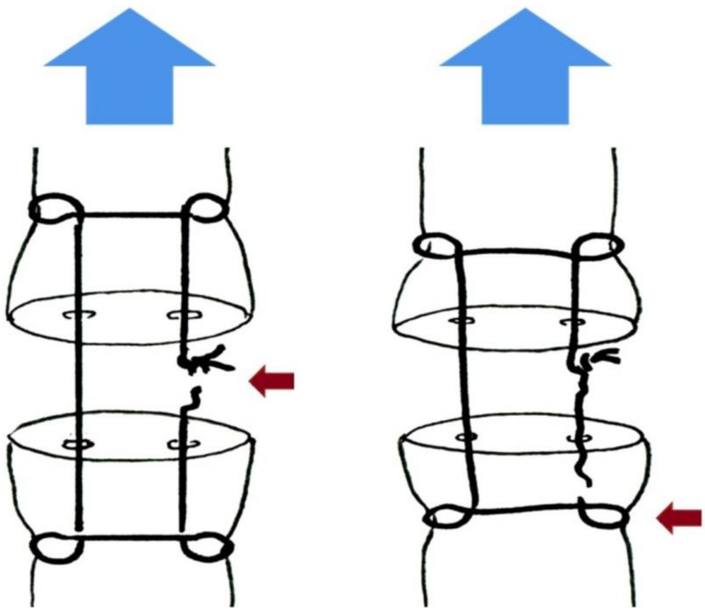

Fig. 7.- Location of breaks in material. (left) sutures at 10 mm; (right) sutures at 5 mm.

the tendon on the side on which the force was applied, (coinciding with a drop in the load level) and became trapped at the same level as the loop (when the load level again rose) and frequently caused a second break in the other longitudinal stitch in Series 3 and 5. Sometimes it caused the strand to untie at the distal end, which generally happened in Series 2 and 4.

The sequence of failure from breakage during the study, first in the peripheral epitendinous and finally in the core (Kessler) suture, suggest us that better gap tolerance is provided by core than peripheral sutures and highlights the latter's importance in preventing the formation of the gap.

Deformation. The following conclusions can be drawn from the analysis carried out with the mathematical model:

In the series without an epitendinous suture, the deformation absorbed by the core suture increases with the distance from the cut tendon edge; it absorbs 93% of total deformation (at time of breakage) when it is placed at 5 mm and 96% when it is at 10 mm from the cut edge. The tendon itself absorbs 7 and 4% of the deformation, respectively.

In the series containing an epitendinous suture, the percentage of stretching absorbed by the tendon is higher than when this suture is omitted. When the core suture is at 5 mm, the tendon absorbs 8% of the total deformation (7% with no epitendinous) and 12% when it is at 10 mm (4% with no epitendinous). The core suture reduces its percentage of total absorbed deformation, regardless of where it is placed, absorbing 92% at 5 mm and 88% at 10 mm, as compared to 93 and 96% with no epitendinous suture. The epitendinous absorbs deformations very similar to those of the core suture, no matter where the latter is positioned, with values of 92 and 87%, respectively.

Load. On studying the series performed at 5 and 10 mm with no peripheral we found no significant difference on the breaking load, with mean numerical values of 22.13 N and 16.25 N. We didn't find significant differences between those performed at 5 mm with and without peripheral. There were, however, significant differences (P=0.003) between the sutures performed at 10 mm with and without peripheral. In general, the stretching force required to break the series tied with a peripheral show a numerical value of 32.65 N, which is almost twice than that of those without a peripheral (18.77 N). Applying the model predicts a greater load to be supported by the peripheral than the core suture, whether this is placed at 5 mm (in this case the peripheral supports 71% of the total load) or 10 mm (76% of total load on peripheral suture).

Gap. In our series there were no significant differences in the final gap at the time of breakage, with mean values around 4.52 mm in the series sutured at 5 mm and 4.71 mm in the series sutured at 10 mm. Neither did we find significant differences between the series with core suture only and those with an additional peripheral epitendinous, which had similar mean numerical values of 5.00 and 4.50 mm, respectively. There were however significant differences in the relationship between strength and gap in favor of the series including epitendinous sutures, which withstood higher loads before the gap had started to develop at a later time.

DISCUSSION

The results obtained from this study show that the *in vitro* behavior of sutured tendons varies according to whether or not an epitendinous suture is included, and also that the mechanical behavior of the normal intact tendon is considerably different from that of the tendon with a core suture both with and without an epitendinous suture. The shape of the curves obtained when a peripheral suture is added is closer to those obtained with intact tendons. This suggests firstly, as reflected in Kastelic’s mathematical model (Kastelic et al., 1980) that the tendon fibers that take the first loads are the peripheral and secondly that the tendon plays a greater role because of a better anchorage.

The epitendinous suture improves the response of the sutured tendon, which raised by an average of 1.2 and 1.6 times (with the core suture at 5 or 10 mm, respectively) the linear stretching modulus and the breaking load by 1.54 times (54%). It is also closer to the characteristic force strain curve of the intact tendon, clearly presenting a first non-linear deformation zone of approximately the same amplitude as the intact tendon (giving mean values of 2.5% in sutured tendons with an epitendinous, against 2.8% in intact tendons). The epitendinous peripheral suture also has the effect of reinforcing the core suture. Applying the model to the values considered predicts higher forces than on the core suture itself, which explains why the suture always starts to fail at the peripheral. This observation agrees with the findings of the forementioned model (Kastelic et al., 1980) which predicts that the peripheral tendon fibers will come into action before the central fibers. This load supported by the peripheral suture increases with the length of the core suture and indicates the importance of the peripheral suture, which has higher resistance when placed at 10 mm.

Other authors (Alavanja et al., 2005; Moriya et al., 2010; Moriya et al., 2012) found that there was no difference between 3-0 or 4-0 tendinous core sutures.

Early motion methods (by active flexing of the affected muscle) can cause a gap to appear which will be associated with the formation of more collagenous tissue between the cut tendon ends, slower maturing and a weaker repair. However, gradually applying tension to the repair area, besides reorganizing the collagen, seems to be the best way to obtain satisfactory functional results and a rapid increase in resistance.

Whatever the type of suture used, the load applied to the sutured tendon finally caused the same gap at the time of breakage.

From our work it can be seen that reducing the amount of material by shortening the longitudinal stitch (situating the cross-stitch at 5 mm instead of 10 mm) has no effect on the design's mechanical resistance and does not significantly improve the gap. In the series with a core suture plus peripheral, increasing the length of the longitudinal stitches means they absorb less deformation, as does the peripheral component, and also transfers some of the load from the core to the peripheral suture. Conversely, the shorter the distance from the core suture the higher the deformation supported by both the core and the peripheral sutures, although this has little impact on the total resistance of the design. We therefore propose situating the core suture cross-stitch at approximately 10 mm from the tendon edge (Gil Santos, 1993).

In agreement with some other authors, we believe that the gap depends more on the number and configuration of the anchorages and to a lesser extent on the length and stretching qualities of the material employed (Mashadi and Amis, 1991). Also, the importance of the distance of the locking loop (locking cross-stitch) in 4-strand sutures has been pointed out; 4 mm locking stitches provide higher resistance to gap formation and greater axial loads in the tendon than 2 mm locking stitches (Alavanja et al., 2005; Peltz et al., 2011).

The strength of the repair is known to be proportional to the number of longitudinal stitches crossing the repair zone (Winters et al., 1998; Barrie et al., 2000; Cao and Tang, 2005; Tang et al., 2005; Cao et al., 2006; McLarney et al., 1999; Xie et al., 2005) and that it is also affected by the size of the locking loops, so that the grasping force is in direct relation to the diameter of the loop (Xie et al., 2005) We are of the opinion that designs should contain at least 4 longitudinal passes and include 2 or 3 mm grasping loops.

Surgical repairs on flexor tendons should be performed with the minimum of carefully controlled actions (Moriya et al., 2010a; Moriya et al., 2010b; Moriya et al., 2012), aided by optical magnification in the most delicate stages, such as when inserting the correct peripheral suture.

We advise using a 4-0 core suture placed at 10 mm from the severed tendon and adding a 6-0 running peripheral to double the strength in absolute values. Knots should be tied parallel to the stitch in a DSD design with a minimum of three, which are less likely to become untied. If more than three are applied the knots will hold but the suture may rupture (Gil Santos et al., 2012). We would like to add that the first signatory of this paper in his clinical practice usually adds a fourth double knot in the opposite direction DSDD to ensure the safety of the design. Anyway, the suture strength can also decrease because of other factors as the torsion of monofilament suture (Hennessey et al., 2012).

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CONFLICT OF INTEREST STATEMENT

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