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A2-PULLEY RECONSTRUCTION: A COMPARISON OF THREE TECHNIQUES IN A CADAVERIC MODEL AND REVIEW OF THE LITERATURE

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ABSTRACT

Reconstruction of flexor tendon pulleys presents serious problems for the hand surgeon. The clinical result after reconstruction efforts in a flexor tendon-pulley unit depends on restoration of grip strength and active range of motion of the finger. Eight forearms were used to evaluate excursion resistance by range of motion and strength resistance of three different A2 pulley reconstruction (Bunnell's, modified Odobescu technique, pulley venting). The results of the in vitro study of excursion resistance and strength resistance of pulley reconstruction demonstrated that the three techniques have similar results, Bunnel's one just brought a better flexion for PIP joint flexion but pulley venting can be considered a second choice for that patients who has the anatomical absence of palmaris lounges (15% of people). The triple loop can be considered as the best choicefor A2 pulley reconstruction, in terms of strength and articular range of motion, in that cases where the techniques in not affordable, pulley venting can be considered a solid second choice for its results similar to the triple loop techniques, for the absence of tendon sacrifice and for the fast execution time.

KEY WORD: *pulley, pulley venting, free tendon loop, tendon gliding, cadaveric model*

INTRODUCTION

The digital flexor sheath pulley system (Fig.1) is a structure that permits normal and efficient flexor tendon function (1). This system is composed of a superficial retinacular and a deep synovial component. The pulleys are made of fibrous

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tissue, which encircle the flexor tendons forming a fibre-osseous channel which keeps the tendons adjacent to the phalanges, this for transferring a translational force generated from the muscle-tendon unit into a rotational moment on the phalanges. In the fingers there are 5 annular (A1-A2-A3-A4-A5) and 3 cruciate (C1-C2-C3) pulleys in descending order from proximal to distal. The A2 and A4 pulleys insert directly into bone, the A1, A3, and A5 insert mostly into volar plate, and with the cruciate pulleys, permit compression without impingement and expansion during finger flexion and extension. A1, A3, and A5 pulleys are located over the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, respectively.

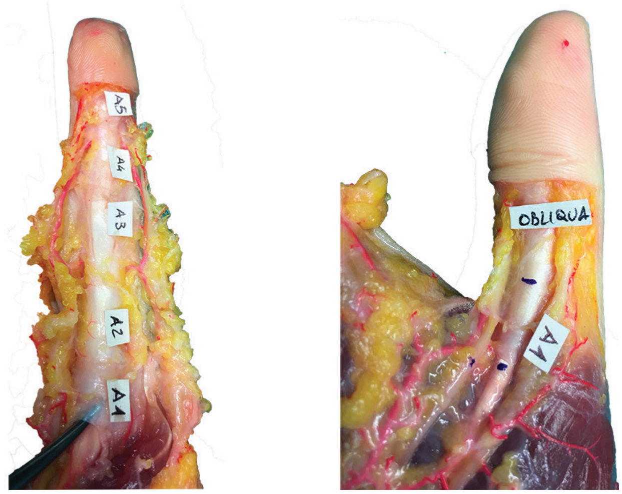

Fig. 1. *Pulley system anatomy.*

The cruciate pulleys C1, C2, and C3, lie between the annular pulleys. Proximal to the A1 pulley lies the palmar aponeurotic (PA) pulley, which is composed of transverse ligament of the palmar aponeurosis attached to the underlying septa of Legueu and Juvara, forming an arch over the flexor tendons superficial. For the thumb 4 pulley system components were described: A1, Av, oblique, and A2 pulleys. The A1 pulley lies over the MCP joint, the oblique pulley runs from proximal ulnar to distal radial over the proximal phalanx, and the A2 pulley is located over the interphalangeal joint. The Av (variable annular) pulley, has now been characterized. First reported in 2012, Schubert and colleagues (2) found this pulley to be present in 93% of cadaver specimens with 3 possible orientations: transverse, oblique, or continuous with the A1 pulley. Because of the historic importance of A2 and A4 pulleys, most surgeons suggest their preservation, repair, or reconstruction. Many surgical techniques have been described for pulley reconstruction to restore hand function (3). The reconstruction of pulleys, both in trauma injuries and tendon surgery, is necessary to avoid bowstringing (4) but above to preserve the natural tendon excursion and to preserve the tendon power. In general, conservation and reconstruction of A2 and A4 pulleys are recommended even if the venting of part of A2 pulley or the entire A4 pulley is now a key point to achieve an optimal result in the tendons sliding (5, 6). In this study, we want to report the effect of three different types of A2 pulley reconstruction on cadaveric specimens and evaluate if there are or not difference in sense of degrees of flexion reached which can lead us to the choice of one respect another.

MATERIALS AND METHODS

Cadaveric dissection

An anatomic study of the pulley was undertaken using 8 forearms from fresh cadavers. None of the specimens had any history of trauma. Dissection was conducted under x3.5 loupe magnification to identify the pulley system under the supervision of support personnel. The arm was dissected from the proximal volar part of the wrist to the pulley, the proximal radio-ulnar joint was secured to prevent rotation of the forearm. The forearms were dissected until the level of the musculotendinous junction, to identify the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) tendons associated with each digit.

Model of pulley reconstruction

Three methods of pulley reconstruction were studied (Fig. 2):

Pulley Reconstruction Using Free Tendon Graft (Triple loop) (7, 8) (Fig. 2A). This technique is made using tendon material, taken usually by the palmaris lungus, when present. In his original description, the pulley graft was placed superficial to the extensor apparatus in the middle phalanx and deep to the extensor mechanism. Although this type of pulley may be bulky, it does not seem to have an adverse effect on the extensor system.

Pulley Reconstruction Using Flexor Digitorum Superficialis Tendon with a maintained distal attachment (FDS slip).

We modified the original technique of Odobescu and colleagues, that use the FDS for A4 pulley reconstruction (9) (Fig. 2B). If the FDS tendon tail is long enough, it may be used as a pulley. In this technique, the distal attachment is preserved, and the free proximal end is sutured over the implant onto the contralateral side. It may be sutured to either periosteum or the original pulley rim or fastened via small holes drilled into bone.

Pulley Venting (10, 11) (Fig. 2C) is made with enlargement of pulley to improve the gliding of repaired flexor tendon. Venting incision is made with an incision on the proximal ulnar half parallel to the bone and. Another incision is distally on the opposite side. The central part of the pulley is cut in a vertical "Z" shape and then the two part of the pulley are sutured.

Technique details

To standardize the reconstruction technique, all pulleys were sutured with 4-0 non-reabsorbed monofilament. 24 fingers, including 8 index fingers, 8 middle fingers, 8 ring fingers from 8 cadaver specimens, were used in each in vitro model. A cross incision was made through the synovial sheath from the A2 pulley to the A5 pulley with the fingers in full extension. The FDP tendon was then pulled up to obtain the complete flexion of the PIP and DIP to verify the correct scrolling of the tendon. With the finger in full extension, the FDS and FDP tendons of each finger were sutured side to side and attached to the S-shaped hook of the dynamometer (Fig. 3).

After, we cut the A2 pulley of the II-III-IV finger and reconstruct each finger in the following techniques):

II FINGER:A length of another tendon passed around the proximal and middle phalanges as triple loop (Fig.4a)

III FINGER: slip of flexor digitorum superficialis with a maintained distal attachment (Fig.4b)

IV FINGER: Direct suture with Pulley Venting (Fig.4c)

Biomechanical analysis

For each finger was evaluated the degree in flexion with intact pulley, with pulley cut and after the pulley reconstruction. The range of motion was measured using a finger goniometer. The

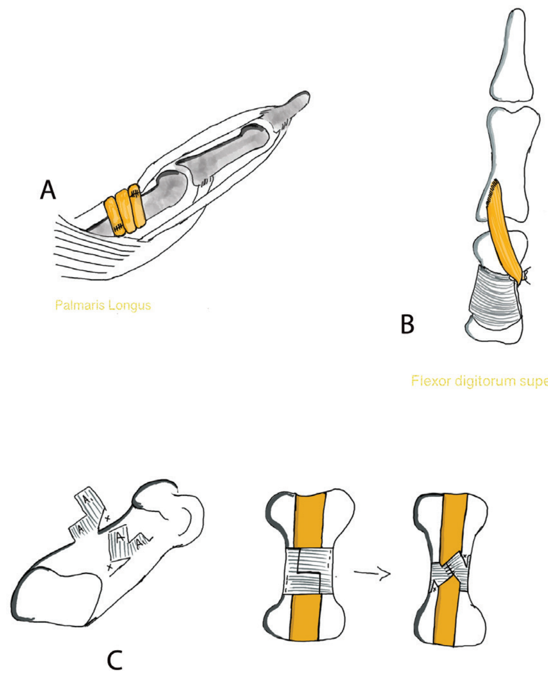

Fig. 2. *Three pulley reconstruction procedures (A) A tendon passed around the proximal phalanx as a triple loop; (B) Flexor digitorum superficialis with distal attachment; (C) Pulley venting.*

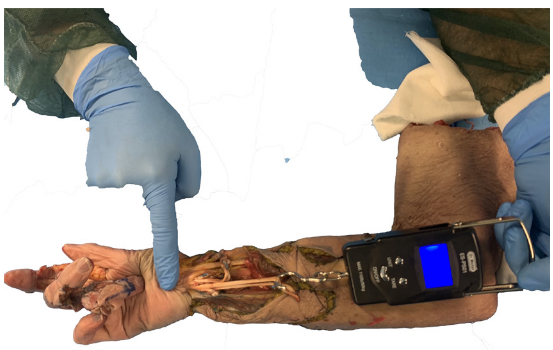

Fig. 3. *The FDS and FDP tendons sutured side to side and attached to the S-shaped hook of the dynamometer.*

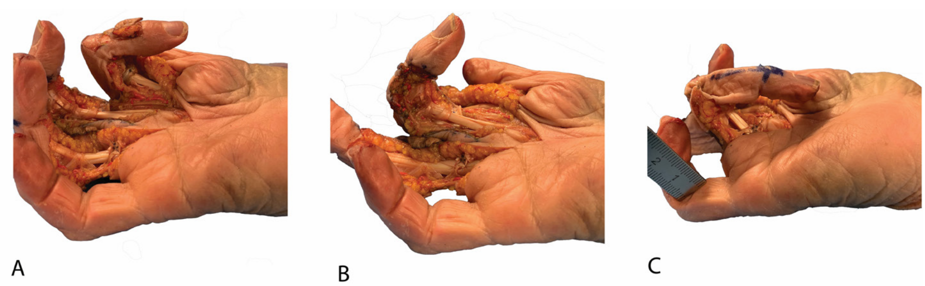

Fig. 4. *Cadaver Specimen of three pulley reconstruction (**A**): triple loop technique; (**B**): flexor digitorum superficialis slip with a maintained distal attachment (**C**): pulley venting.*

angles of the MCP, PIP, DIP joints were measured in maximum flexion and extension, with the forearm and the wrist in neutral position. The Total Active Motion (TAM) of the American Surgery Society of the Hand (ASSH) and both Strickland classification systems (12-15) were applied (Table I A, B). Before and after the A2 pulley reconstructions, we applied a constant strength of 5Newton using a dynamometer (Dr.Meter ES-PS01) (Fig.3) and we evaluated if the pulley resist to a strength >10 N (more than the strength needed for transportation of a six pack of waters bottle).

Statistical analysis

Measurements were performed before and after reconstruction and data were evaluated according to the ANOVA test. The differences before and after the reconstruction were analyzed for statistical value via the t-test. The statistical analysis threshold was set at p-values, significant at <0.05. Statistical Analysis Software (Xlstat add-in excel) was used to conduct two-tailed Student's T, Pearson index, Kolmogorov-Smirnov test.

RESULTS

A total of 24 fingers, for 72 articulations were evaluated. We investigated which structure failed at the maximum load and we got only 1-vented pulley broken because it was too close to the bone, with a calculated bowstringing of 2mm. The other 7-vented pulley were sutured leaving a 3mm bowstringing which showed to be enough to avoid the pulley rupture. The PIP joint was the most affected by the A2 pulley cut, in venting and tendon graft reconstruction it got a range of motion in flexion comparable to the normal pulley. In the 8-pulley reconstructed with triple loops technique it was showed a constant bowstringing of 2 mm for each finger treated. The 8-reconstructions made with FDS slip showed the worst result ending in an important bowstringing of 6-7 mm , losing his containingfunction (Table I).

Comparing the degrees of flexion before and after reconstruction, we checked if there were statistically differences for type of reconstructive techniques and we obtained for Triple loops reconstruction not significative difference in MCP flexion (p=0.1), neither in DIP flexion (p= 0.45), significative PIP flexion (p=0.02). For reconstruction with FDS slip we got not significative difference in MCP flexion (p=0.45), neither in PIP flexion (p= 0.26) or DIP flexion (p=0.06). For reconstruction with pulley venting we got not significative difference in MCP flexion (p=0,41), neither in DIP flexion (p= 0.36), significative PIP flexion (p=0.007). The TAM and Strickland test also didn't show statistically significative difference for FDS strand and venting techniques, while showed significative result in tendon loop technique (p=0.05) (Table II).

At 10N load, 23-pulley didn't break out, the only broken pulley was the 1 reconstructed with the pulley venting techniques which got the bowstringing of 2mm.

DISCUSSION

The Pulley system reconstruction is a fundamental aspect for a successful reconstruction of the flexor tendon injury (16, 17). The muscular belly of flexor profundus has a maximum shortening capability, because their excursion is constant, the pulley system is charged with maximizing the tendons' ability to generate flexion. Intact pulleys prevent tendon translation to palmar side. If the pulley is resected, the tendons displace volarly, and the maximum range of motion in flexion is decreased.

Reconstruction of flexor tendon pulleys is an important problem for the hand surgeon. Most pulley ruptures can be successfully treated conservatively with full return to preinjury activity. When surgery is necessary, pulley reconstruction results in the best outcomes. Nowadays there is still not actual evidence of which techniques is the best option. In addition to the pulley reconstruction techniques studied in this study, other techniques such as the Kleinert/Weilby technique that is a technique involving weaving a tendon through the "always-present fibrous rim" of the pulley being reconstructed. Usually is used the tail of the superficialis tendon, but if not available, a tendon graft may be used instead. This technique has the advantage that it affords the surgeon good control over setting tension in the reconstructed pulley (18). The Karev—belt-loop is a technique that performed two transverse incisions in the volar plate and sliding the flexor tendon through the so called "belt loop" formed between the two incisions. Because the tendon must be passed through the belt loop, this technique can be used only in the presence of an adjunctive flexor tendon repair or tendon graft/implant and

Table I. *Dgree in flexion of all fingers with intact pulley and after A2 pulley reconstruction with different techniques.*

Hand #1	MF pre	MF post	IPP pre	IPP post	IPD pre	IPD post	BOWSTRIN GING	Rupture at 10 N application
IInd	0/55	0/55	0/60	0/60	0/40	0/40	2mm	No
IIIrd	0/60	0/60	0/65	0/65	0/80	0/80	6mm	No
IVth	0/40	0/40	0/45	0/45	0/40	0/40	3mm	No
Hand #2	MF pre	MF post	IPP pre	IPP post	IPD pre	IPD post	BOWSTRIN GING	Rupture at 10 N application
IInd	0/70	0/80	0/120	0/110	0/45	0/65	2mm	No
IIIrd	0/70	0/90	0/90	0/100	0/45	0/50	7mm	No
IVth	0/90	0/115	0/110	0/100	0/65	0/90	2mm	Yes
Hand #3	MF pre	MF post	IPP pre	IPP post	IPD pre	IPD post	BOWSTRIN GING	Rupture at 10 N application
IInd	90	90	110	110	75	60	2mm	No
IIIrd	100	85	110	105	105	60	6mm	No
IVth	110	95	115	115	75	50	3mm	No
Hand #4	MF pre	MF post	IPP pre	IPP post	IPD pre	IPD post	BOWSTRIN GING	Rupture at 10 N application
IInd	70	65	120	110	45	45	2mm	No
IIIrd	0/70	0/70	0/90	0/80	0/45	0/45	6mm	No
IVth	90	90	85	80	75	70	3mm	No
Hand #5	MF pre	MF post	IPP pre	IPP post	IPD pre	IPD post	BOWSTRIN GING	Rupture at 10 N application
IInd	0/80	0/75	0/120	0/115	0/90	0/80	2mm	No
IIIrd	0/80	0/75	0/110	0/105	0/90	0/80	6mm	No
IVth	0/100	0/100	0/90	0/90	0/90	0/80	3mm	No
Hand #6	MF pre	MF post	IPP pre	IPP post	IPD pre	IPD post	BOWSTRIN GING	Rupture at 10 N application
IInd	0/70	0/80	0/120	0/110	0/45	0/65	2mm	No
IIIrd	0/70	0/90	0/90	0/100	0/45	0/50	6mm	No
IVth	0/90	0/115	0/110	0/100	0/65	0/90	3mm	No
Hand #7	MF pre	MF post	IPP pre	IPP post	IPD pre	IPD post	BOWSTRIN GING	Rupture at 10 N application
IInd	100	100	120	120	85	80	2mm	No
IIIrd	100	95	120	110	85	75	6mm	No
IVth	110	105	130	120	100	95	3mm	No
Hand #8	MF pre	MF post	IPP pre	IPP post	IPD pre	IPD post	BOWSTRIN GING	Rupture at 10 N application
IInd	0/90	0/90	0/110	0/110	0/75	0/60	2mm	No
IIIrd	0/100	0/85	0/110	0/105	0/105	0/60	6mm	No
IVth	0/110	0/95	0/115	0/115	0/75	0/50	3mm	No

Table II. *Tam and Strickland test before and after A2 pulley reconstruction.*

	FREE TENDON LOOP				FDS SHEET				VENTING			
	STRICKLAND		TAM		STRICKLAND		TAM		STRICK LAND		TAM	
HAND N°	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
1	57.1	57.1	58.5	58.5	82.8	82.8	77.3	77.3	48.5	48.5	47.1	47.1
2	94.2	60	88.63	62.2	77.1	85.7	77.3	90.57	100	108.5	100	115.1
3	105.7	97.1	103.7	98.1	122.8	94.2	118.8	94.3	108.5	88.5	113.2	94.3
4	94.2	88.5	88.6	83.0	77.1	71.4	77.3	73.5	91.4	85.7	94.3	90.5
5	120	111.4	109.4	101.8	114.2	105.7	105.6	98.1	102.8	97.1	105.6	101.8
6	94.2	100	88.6	96.2	77.1	85.7	77.3	90.5	100	114.2	100	118.8
7	117.1	114.2	115.1	113.2	117.1	105.7	115.1	105.6	131.4	122.8	128.3	120.7
8	105.7	97.1	103.7	98.1	122.8	94.2	118.8	94.3	108.5	94.3	113.2	98.1
p-value		0.05		0.07		0.07		0.2		0.2		0.3

not for simple pulley reconstruction around an intact tendon (19). Moreover, the Lister's technique harvests a segment of the extensor retinaculum, which is reversed and then passed around the phalanx (20). The major disadvantage of this technique is that a normal portion of the extremity must be violated to harvest the retinaculum. The main advantage is that the retinaculum provides a smooth gliding surface producing the lowest amount of resistance among the reconstructive techniques. In this study, we want to report the effect of three different types of A2 pulley reconstruction on cadaveric specimens and evaluate if there are or not difference in sense of degrees of flexion reached which can lead us to choose of one respect another.

The main purpose of this study was to compare the range of motion of each finger joint before and after the A2 reconstruction and to compare the biomechanics activity to evaluate which techniques gives the best result. Our study showed that Pulley venting has a different strength depending on how tight the suture is made, we showed that a laxity that leads on a bowstringing of 3 mm preserves the pulley, such as the strength goes on the A1 intact pulley, what make us think that in A1 and A2 reconstruction, a double pulley venting could not be the best choice; however, in the A2 isolated pulley reconstruction the techniques showed similar results through the evidence of not significant difference among that various construction tecniques. The modified Odobescu techniques gave worse result due to a more mm bowstringing because the distal part of the FDS strand left attached to his insertion on F2, while the Tendon graft techniques gave results similar to the venting, with a lower grade of bowstringing and a better result for IPP joint flexion. Nishida et al. in a 1998 (21) compared different reconstructive methods intrasynovialand extrasynovial, and found out the best reconstructive method, from the point of view of friction, is to loop the pulley reconstruction around bone, as in Lister's or Bunnell's technique. The around-bone method is also the strongest reconstruction (22, 23). Considering our result, there is not an evidence that one techniques is better than another, the only significative result is about TAM score in tendon loop repair, that appears in our experience as the most valuable technique. Considering that the tendon graft requires the presence of palmaris longus tendon, pulley venting can be considered like a solid choice for A2 reconstruction in that 10-15% of people who doesn'thave the palmaris longus. We also showed that the flexor digitorum superficialis reconstruction is not a reliable procedure, although the easy execution and the small tendon sacrifice.

The limit of the study is due to the cadaveric experiments, in which is not possible to evaluate the follow up; there is no possibility in cadavers to evaluate the effectiveness of bulky reconstruction such as the tendon graft; and it's not possible to evaluate if a continues stimulation due to the tendon glidingcan bring to pulley rapture, in particular in the pulley vented.

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