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1 The «RoC» suture technique to allow early active rehabilitation in
2 flexor tendon repair: a biomechanical study

3 **Marie CASTOLDI, MD, Federico Solla, MD, Olivier Camuzard, MD PhD Martine**
4 **Pithioux, PhD, Virginie Rampal, MD PhD, Olivier Rosello, MD**

5 **ABSTRACT**

6
7 **Purpose.** Current flexor tendon repair techniques do not provide sufficient tensile strength to
8 allow immediate active unprotected rehabilitation. The «RoC» repair, a new 4-strand
9 suture technique, is proposed to improve biomechanical properties, combining a high tensile
10 strength and a low gliding resistance without causing suture pullout by tendon laceration.

11 Our hypothesis is that the RoC technique can reach an ultimate tensile strength of 140N, and a
12 higher tensile strength than the Adelaide technique.

13 **Methods.** Four groups of 10 porcine flexor tendons were sutured with the RoC or
14 Adelaide technique, and with a 3-0 Polypropylene or Dyneema suture. An axial traction test
15 to failure (Instron machine) was administrated to each tendon to measure ultimate tensile

16 strength. **Results.** With the Dyneema suture, median ultimate tensile strength was 145N
17 for the RoC technique and 80N for Adelaide ($p < 0.01$). RoC tendons were 1.8 times more
18 resistant than Adelaide tendons with the Dyneema suture, and 1.2 times more resistant with

19 Polypropylene. **Conclusion.** Tendons repaired with the RoC technique and Dyneema suture
20 exceeded a tensile strength of 140N. The ultimate tensile strength was superior to that of
21 Adelaide technique regardless of the suture material.

22
23
24 **Key words**

Flexor tendon, hand injuries, suture techniques, tensile strength

25 INTRODUCTION

26 Hand flexor tendon injuries are frequent and their treatment holds several challenges. Restoring
27 satisfactory function after tendon repair requires a sufficient tensile strength and low gliding resistance
28 to allow for early active mobilization ^{1,2}. Tensile strength of the repair is affected by the number of
29 strands, the caliber of the core suture, the suture material (braided or not), surface treatments, size and
30 shape of the needle, the knot configuration, the loop configuration and the number of anchor points ³⁻⁷
31 . Improvements in suture materials and repair techniques have led to stronger repairs. ^{3,8-10}. Despite these
32 advances, conventional tendon repair techniques do not provide sufficient tensile strength to
33 immediately allow unprotected mobilization ^{1,3,4,8,11,12} . Protected active rehabilitation implies
34 permanently wearing a splint during the six weeks of tendon healing. Even then, adhesions, stiffness,
35 and repair-site gapping remain a frequent outcome ^{8,12-14} There are three possible causes of tendon
36 repair failure ²: suture breakage, knot failure, and suture pullout by tendon dilaceration.

37 The axial tensile force applied to a repaired flexor tendon during full extension of the finger
38 and active flexion is unknown from the literature; the active flexion of a healthy finger in vivo
39 is up to 28N¹⁵; Savage ¹⁶ postulated that the strength of a flexor repair should be 5 times greater
40 than the active flexion force (i.e. 140N).

41 The most common techniques are a modified 4-strand Kessler technique, Becker, Adelaide or
42 Strickland, with several variants; their biomechanical properties have been studied with in vitro
43 tensile tests (on cadaver or porcine tendons) and, more rarely, in vivo ^{2,4,8,17-19}.

44 An extensive literature review in 2000 defined the 6 characteristics of an ideal suture
45 technique². Accordingly, the sutures have to be easily placed in the tendon with secure suture
46 knots, allowing for a smooth juncture of the tendon ends, minimal gapping at the repair site,
47 minimal interference with tendon vascularity, and a sufficient tensile strength throughout
48 healing. Following these criteria, the Adelaide repair technique¹ (also known as locked
49 Cruciate) can be considered a gold standard, because it provides the highest tensile strength in

50 in vitro studies (up to 120N⁹). However, in a recent study, tendons repaired with a helical 6-
51 strand Cruciate had a greater ultimate tensile strength (65N) than with the Adelaide technique
52 (46N)²⁰. Barbed sutures seem to provide a higher tensile strength, up to 64N, but largely below
53 the 140N requested for active unprotected rehabilitation ^{21,22}.

54 We propose a new 4-strand repair technique, the “RoC” technique, to combine a high tensile
55 strength and a low gliding resistance without causing suture pullout by tendon laceration.

56 The objective of this study is to compare, in vitro, the biomechanical properties of this new
57 technique with those of the Adelaide repair technique. We hypothesized that the RoC repair can
58 reach an ultimate tensile strength of 140N, in order to withstand an immediate active
59 unprotected rehabilitation protocol.

60

61 2. MATERIALS AND METHODS

62 2.1. Study protocol

63 This study followed the design of published biomechanical evaluations of in vitro porcine
64 flexor tendon repair techniques ^{4,9,18,23}. The use of animal tissues complied with the guidelines
65 of the authors' institution, the National Institutes of Health, and French law on the use of
66 laboratory animals.

67 Fresh porcine forelimbs were purchased and dissected. Both flexor tendons were harvested
68 from each forelimb, with an average cross-sectional area of 20 mm² and a minimum length of
69 10cm, allowing them to be installed in the clamps of the traction machine. A clean cross-tendon
70 cut with a scalpel simulated a traumatic section. To ensure consistency of the technique, section
71 sites and points of entry of the core suture were pre-marked on the tendons, and all sutures were
72 performed by a single surgeon (MC).

73 Forty porcine flexor tendons were randomly allocated to 4 groups of 10 tendons (figure 1), cut
74 transversally then repaired and tested in axial traction. The core suture (RoC or Adelaide) was
75 performed with a 3-0 suture, either Prolene® (Ethicon® NJ 08876 USA) or Dyneema
76 (KastKing®), and reinforced with a peripheral epitendinous running suture with a Prolene 6-0,
77 2mm from the section site. After the suture, the tendons were immediately stored in a freezer
78 at -80°C²².

79

80 2.2. Surgical technique: the “RoC” repair

81 The knots used for mountaineering inspired the loop configuration of this new repair
82 technique, which owes its name to the initials of the creators and to a regional summit in the
83 region of the authors. The basic pattern of the RoC repair is a 3-dimensional figure of eight
84 with 4 anchors in the 3 planes of space. This pattern is repeated with two sliding sutures on
85 both ends of the tendon, forming a 4-strand repair. The loop configuration is illustrated in
86 figures 2 and 3. For optimal tensile strength, suture tensioning should result in approximately
87 10% shortening of the tendon length at the suture site²⁴. The ends are tied suture by suture
88 and then together in one knot.

89 The gold standard repair technique chosen for comparison in this study was the Adelaide²³,
90 or 4-strand locked cruciate repair (figure 4).

91

92 2.3. Suture materials

93 During preliminary testing, tendons repaired with the RoC technique and Prolene suture failed
94 by suture breakage. Prolene is a non-absorbable polypropylene monofilament suture
95 commonly used for flexor tendon repairs, pre-mounted with a curved taper needle. The
96 observation of suture breakage prompted us to use a stronger suture. In existing studies,
97 repairs with Dyneema suture had the highest tensile strength^{9,10}. Dyneema is a non-

98 absorbable fiber made from ultra-high-molecular-weight polyethylene, a lightweight and high
99 strength material used in arthroplasties since the 1980s and more recently in sutures.
100 Therefore, we used a commercially purchased 100% Dyneema unmounted braid 0.25mm
101 (diameter of a surgical 3-0 suture ²⁵) with a curved cutting-edge needle. Thus, both repair
102 techniques were tested with a 3-0 Prolene (Ethicon®), and a 0.25mm Dyneema (KastKing®)
103 suture.

104 2.4 Outcomes and mechanical testing

105 The primary outcome was the ultimate tensile strength measured in Newtons (N). Secondary
106 outcomes were the 2-mm gap formation force (N), failure mode of the repair (knot failure,
107 suture breakage or suture pullout), stress (ultimate tensile strength divided by the tendon
108 cross-section area, in N/mm²), and stiffness (in N/mm).

109 Mechanical testing was conducted on an Instron 5566A® axial traction machine (Instron
110 Corp, MA) (figure 5A). The tendons were thawed in saline-soaked gauze at 4°C for 24 hours.
111 The dimensions of the tendon were recorded at the suture site and at a healthy site 30mm
112 distal, to calculate the cross-section areas. Both ends of the repaired tendon were mounted
113 into standard clamps. The initial distance between the clamps was set at 40mm for all tendons.
114 Loading was applied to the repaired tendons to a single load-to-failure compression test. After
115 application of a 1-N preload, the tendons were pulled at a constant speed of 10mm/min.
116 Quasi-static loading with prescribed displacements at 1mm per min was applied up to failure.
117 Data were recorded at a rate of 10 Hz. The software (Bluehill Universal, Instron Corp) created
118 a load-displacement curve, from which the ultimate tensile strength was determined (peak of
119 the curve). Stiffness was calculated as the slope of the initial linear section of the curve. A
120 ruler was attached to the upper clamp next to the tendon, and the test was monitored by a
121 high-definition camera in order to determine the 2-mm gap formation force (figure 5B and C).
122 Failure was considered to be the first local maximum before a load decrease was observed on

123 the load-displacement curve. Failure mode was determined by visual examination of the
124 tendons, photographed after testing.

125

126 2.5 Statistical Analysis

127 The Shapiro-Wilk test was used to ensure that the cross-section areas of the tendons were
128 normally distributed. The non-parametric Mann-Whitney test was used to compare the numeric
129 outcomes (mechanical testing results and cross-section areas) between each group. The exact
130 Fisher test were used to compare the failure mode between each group. The alpha risk was set
131 at 5% ($\alpha = 0.05$)²⁶.

132

133 3. RESULTS

134 Gross mechanical testing results are presented in table 1 and compared group by group in tables
135 2 and 3.

136 With the Dyneema suture, median ultimate tensile strength for the RoC technique was 145N.
137 RoC tendons were 1.8 times more resistant than Adelaide tendons with the Dyneema suture,
138 and 1.2 times more resistant with the Prolene suture ($p < 0.01$).

139

140 4. DISCUSSION

141 4.1. Primary outcome - Ultimate tensile strength

142 Tendons repaired with the RoC technique had a significantly higher ultimate tensile strength
143 than tendons repaired with the Adelaide technique, regardless of the suture used (Prolene or
144 Dyneema). The median ultimate tensile strength with RoC and Dyneema exceeded 140N,

145 which was the targeted tensile strength to allow immediate unprotected active rehabilitation.
146 The lower value of the confidence interval was 130N, which is higher than the previous data with a
147 4, 6, and 8-strand techniques^{2,4,8,10,17,19-23,27}.

148 The tensile strength of 140N was not achieved with Prolene suture. RoC repairs with Prolene
149 exceeded the tensile strength of Adelaide by only 11N, and failed by suture breakage in all
150 cases, implying that the resistance of the suture material was the limiting factor. Indeed, RoC
151 tendons with Dyneema gain 82N in ultimate tensile strength compared with Prolene ($p < 0.01$).
152 In a previous study by Lawrence and Davis⁴, repairs with the Adelaide technique reached a
153 mean ultimate tensile strength of 63N with a 4-0 Prolene suture; all their repairs reportedly
154 failed by suture rupture. On the contrary, in our study Adelaide tendons failed by suture pullout
155 in 9 out of 10 cases with Prolene and 8 out of 10 cases with Dyneema. Varying outcomes with
156 Adelaide and Prolene may be attributed to differences in tendon quality, suture caliber, and
157 loading speed during testing.

158 With Dyneema, Adelaide tendons in our study reached 79N, a similar tensile strength to
159 Adelaide with 4-0 Fiberwire in the study by Lawrence and Davis⁴, whereas the maximum
160 tensile strength reported for Adelaide was 119N with 3-0 Fiberwire in the study by Croog et
161 al.⁹ This difference may be explained by the cross-section area of the sutures²⁵: the area of 3-0
162 Fiberwire was 0.083mm^2 corresponding to a standard 2-0 size (USP), whereas the area of 4-0
163 Fiberwire was 0.067mm^2 which is between standard 2-0 and 3-0 size, and that of a 3-0 Prolene
164 was 0.056mm^2 , also between 2-0 and 3-0. By comparison, the cross-section area of 0.25mm
165 Dyneema suture we used would be 0.049mm^2 . This difference in suture caliber between 3-0
166 Fiberwire and 0.25mm Dyneema may explain the higher tensile strength for Adelaide tendons
167 in the study by Croog et al. compared to our study¹⁴.

168 4.2. Secondary outcomes: cross-section area and 2-mm gap

169 There was no significant difference in cross-section area (suture site and healthy site) between
170 the groups. The stress outcome thus mirrored the ultimate tensile strength.

171 The 2-mm gap formation force of RoC repairs was significantly higher than that of Adelaide
172 repairs with Dyneema, but similar with Prolene. As with the ultimate tensile strength, lower
173 resistance of the Prolene suture may explain this outcome. Gap formation (1 to 3mm) has been
174 associated with adhesions and poorer clinical results^{28,29}, but the exact limit for tendon healing
175 remains unknown⁹.

176 4.3 Suture material and failure mode

177 Dyneema is the main component of the most resistant current braided sutures, but also fishing
178 lines, climbing and boat ropes. We selected the most resistant available suture to test the repair
179 technique itself and the knot without limitation related to the intrinsic resistance of the material.
180 While using a Prolene suture for the RoC repair, failure occurred at 63N because of suture
181 breakage. With the more resistant Dyneema suture, RoC tendons failed by suture pullout. In
182 Adelaide tendons repaired with Prolene, suture pullout occurred in all but one case before
183 reaching the maximum resistance of the suture or the knot. Suture pullout was also the main
184 failure mode with Dyneema, but this result may be impacted by the use of a cutting needle.
185 Indeed, the Dyneema suture was used with a separate cutting needle, whereas the Prolene suture
186 has a pre-mounted taper needle. We hypothesize that the RoC repair with a surgical Dyneema
187 suture and mounted taper needle such as Fiberwire would result in few suture pullouts, which
188 may increase the ultimate tensile strength of the repair.

189 4.4. Limitations

190 The main limitation in this study is the use of a non-surgical Dyneema unmounted braid,
191 instead of a surgical Dyneema suture, which was unavailable at the time of the study. The
192 core resistance of the Dyneema suture we used should be identical to that of a surgical suture,

193 but surface treatments and threading techniques can alter the biomechanical properties.
194 Moreover, the use of a separate cutting needle, different in shape and size from the pre-
195 mounted needle of a surgical suture, may have increased the tissue damage during the repair
196 and favored suture pullout. Therefore, these outcomes require further confirmation with a
197 surgical Dyneema suture.

198 Other limitations are the classic limitations of in-vitro biomechanical studies for flexor tendon
199 repair and their extrapolation to in-vivo conditions. The unique axial tensile test fails to
200 account for different speeds and angles of elongation stress, for fatigue after multiple cycles,
201 and for work of flexion, which will be the object of a following study. The use of porcine
202 flexor tendons instead of human cadaver tendons can also constitute a limitation, although
203 most studies about flexor repair have used porcine tendons due to their similarities to human
204 tendons and the easy access to well-preserved tissue. Thus, the next step to evaluate the RoC
205 repair will be a comparative work of flexion study on cadaver hands.

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311 **Legend**

312 Figure 1. Study protocol. Allocation of each group of 10 tendons to a repair technique and a
313 suture type.

314 Figure 2. Illustration of the basic pattern of the RoC repair following passages of the suture in
315 the order of realization (A). Illustration of the completed RoC repair (B).

316 Figure 3. Basic configuration of the RoC repair with Prolene 3-0 suture on the distal end of a
317 porcine flexor tendon.

318 Figure 4. A : Instron 3360 traction machine. B : HD camera and ruler for the 2-mm gap force.
319 C : Example of a tendon sutured with the RoC technique. Simultaneous display of the applied
320 load (236N) and the video image of the tendon and ruler measuring 2-mm gap.

321 Table 1: Mechanical testing in axial traction.

322 Table 2: Statistical comparison of tendons sutured with Prolene suture: RoC versus Adelaide
323 technique (Group A versus C)

324 Table 3: Statistical analysis of tendons sutured with Dyneema suture. RoC versus Adelaide
325 technique (Group B versus D)

326

327

Figure 1: The groups









	Group A	Group B	Group C	Group D
Repair	RoC 	Roc 	Adelaide 	Adelaide 
Material	Prolene 	Dyneema 	Prolene 	Dyneema 

Figure 2

RoC suture: drawing

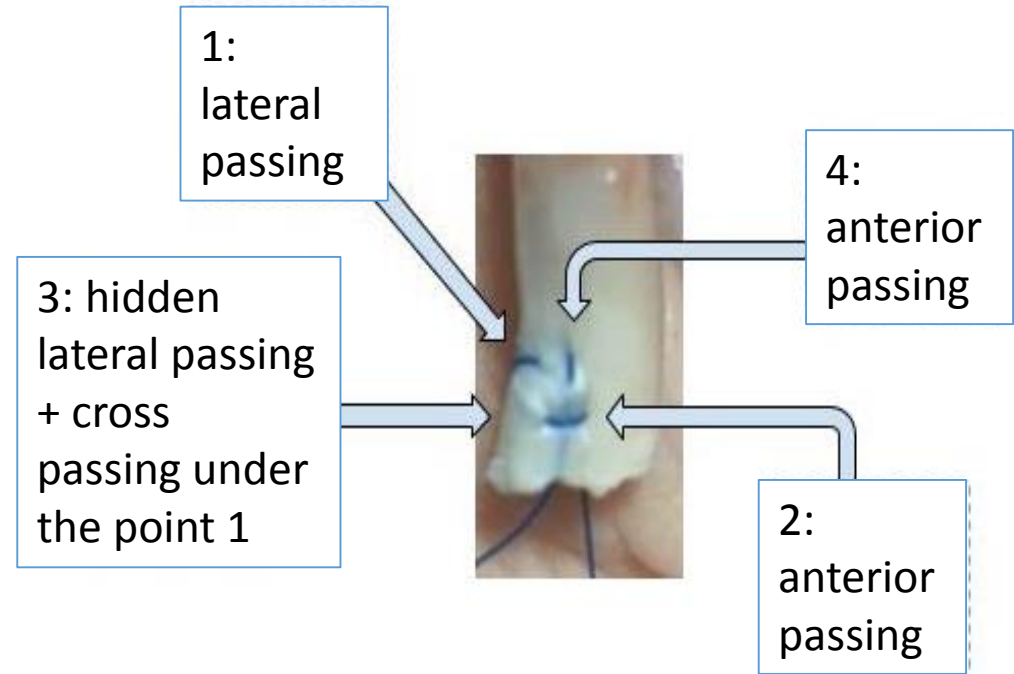
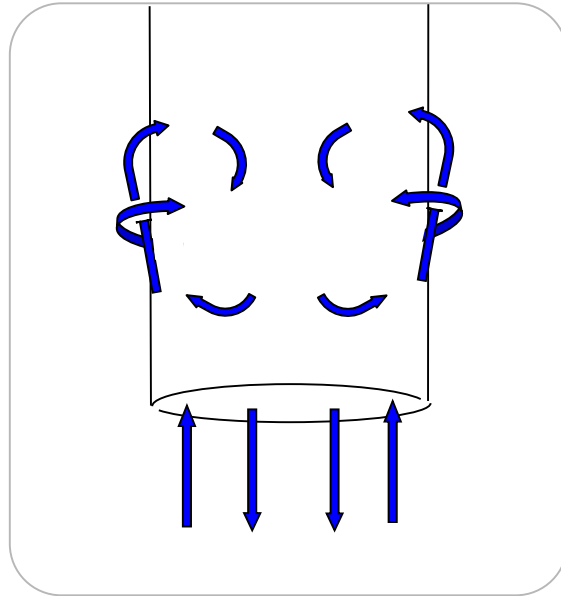
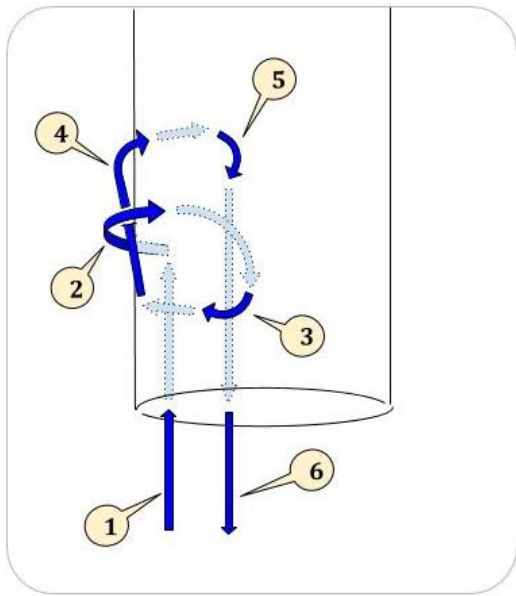


Figure 3

RoC suture: repaired tendon

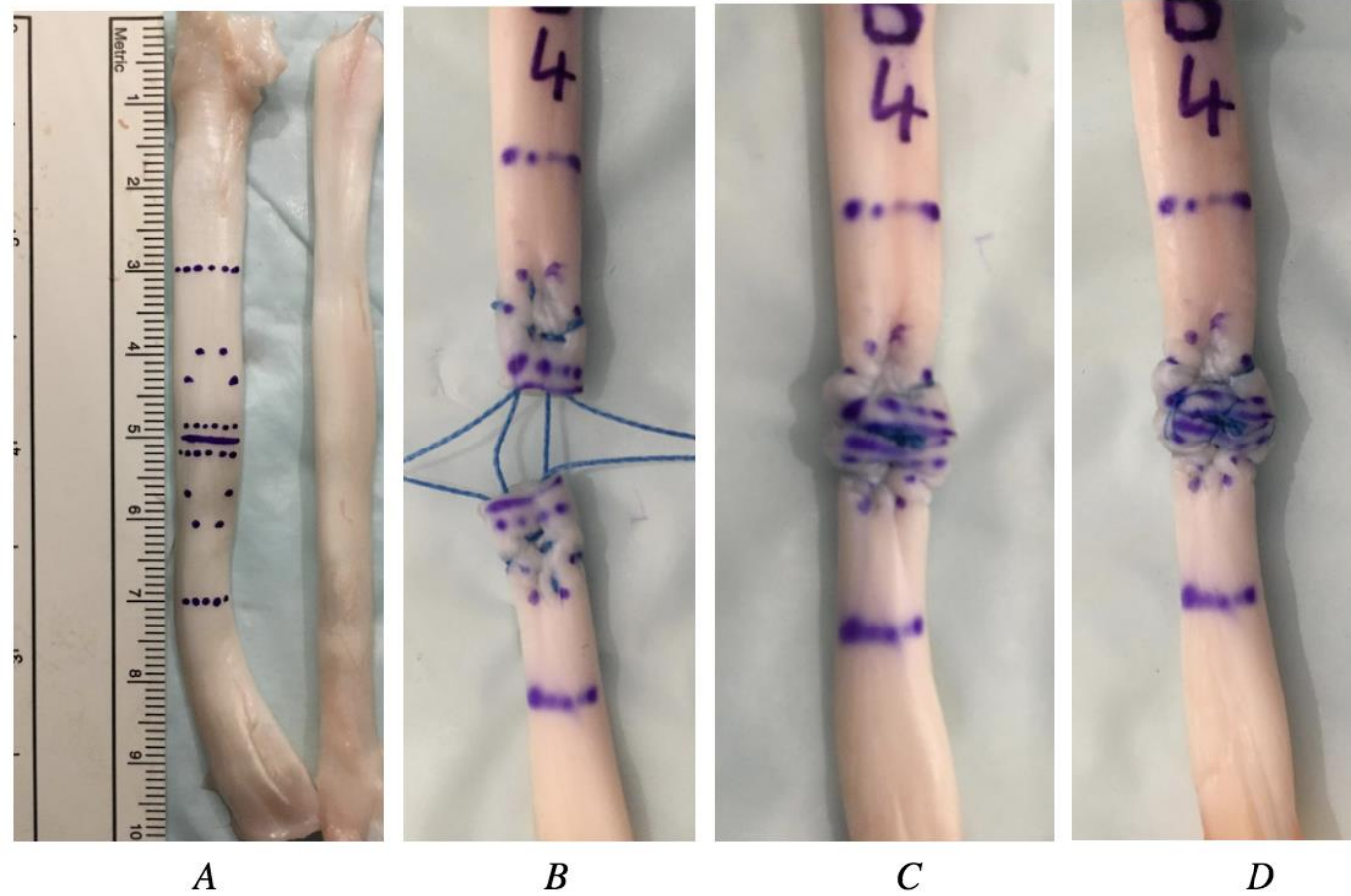


Figure 4:
Instron machine

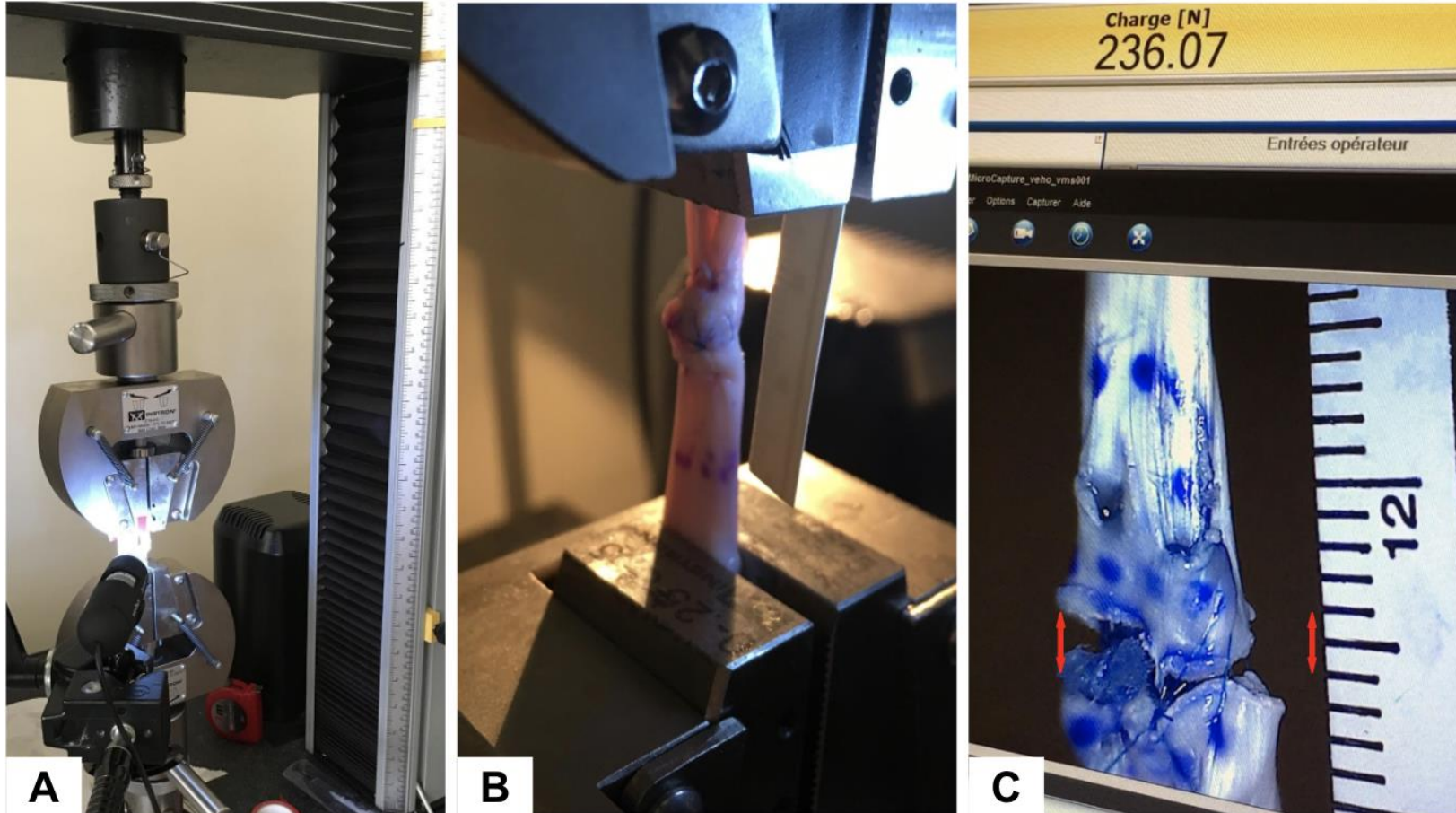


Table 1. Mechanical testing in axial traction. Results are presented for each numeric outcome as Median value [95% Confidence Interval]. Failure mode is expressed as Number of tendons out of 10.

	Group A RoC + Prolene	Group B RoC + Dyneema	Group C Adelaide + Prolene	Group D Adelaide + Dyneema
Ultimate tensile strength (N)	63.6 [59.56 - 69.49]	145.54 [130.96 - 179.03]	52.21 [46.80 - 58.79]	79.76 [72.57 - 88.28]
2-mm gap force (N)	48.00 [43.91 - 54.28]	136.50 [119.23 - 170.76]	47.50 [40.65 - 53.34]	79.00 [71.82 - 87.37]
Stiffness (N/mm)	5.95 [5.30 - 6.73]	14.92 [12.67 - 17.42]	4.48 [4.01 - 4.77]	10.12 [9.27 - 11.62]
Stress (N/mm ²)	2.99 [2.58 - 3.82]	8.70 [7.19 - 9.46]	2.23 [2.06 - 2.66]	4.76 [4.31 - 5.63]
Cross-section area at healthy site (mm ²)	19.93 [17.40 - 25.05]	18.97 [16.37 - 21.41]	22.53 [20.51 - 24.55]	15.56 [13.96 - 19.19]
Cross-section area at suture site (mm ²)	30.29 [25.71 - 40.38]	40.69 [38.89 - 48.65]	37.22 [33.38 - 40.67]	41.97 [37.20 - 49.57]
FAILURE MODE :	<i>n = 10</i>	<i>n = 10</i>	<i>n = 10</i>	<i>n = 10</i>
Suture breakage	10/10	0	1/10	0
Knot failure	0	0	0	2/10
Suture pullout	0	10/10	9/10	8/10

Table 2. Statistical comparison of tendons sutured with Prolene suture: RoC versus Adelaide technique (Group A versus C)

	Group A RoC + Prolene	Group C Adelaide + Prolene	Comparison group A versus C
Ultimate tensile strength (N)	63.6 [59.56 - 69.49]	52.21 [46.80 - 58.79]	p < 0.01
2-mm gap force (N)	48.00 [43.91 - 54.28]	47.50 [40.65 - 53.34]	p > 0.05
Stiffness (N/mm)	5.95 [5.30 - 6.73]	4.48 [4.01 - 4.77]	p < 0.01
Stress (N/mm ²)	2.99 [2.58 - 3.82]	2.23 [2.06 - 2.66]	p < 0.05
Cross-section area at healthy site (mm ²)	19.93 [17.40 - 25.05]	22.53 [20.51 - 24.55]	p > 0.05
Cross-section area at suture site (mm ²)	30.29 [25.71 - 40.38]	37.22 [33.38 - 40.67]	p > 0.05
FAILURE MODE :	n = 10	n = 10	
Suture breakage	10 (100%)	1 (10%)	p < 0.001
Knot failure	0	0	
Suture pullout	0	9 (90%)	

Table 3. Statistical analysis of tendons sutured with Dyneema suture. RoC versus Adelaide technique (Group B versus D)

	Group B RoC + Dyneema	Group D Adelaide + Dyneema	Comparison B vs D
Ultimate tensile strength (N)	145.54 [130.96 - 179.03]	79.76 [72.57 - 88.28]	p < 0.01
2-mm gap force (N)	136.50 [119.23 - 170.76]	79.00 [71.82 - 87.37]	p < 0.01
Stiffness (N/mm)	14.92 [12.67 - 17.42]	10.12 [9.27 - 11.62]	p < 0.01
Stress (N/mm ²)	8.70 [7.19 - 9.46]	4.76 [4.31 - 5.63]	p < 0.01
Cross-section area at healthy site (mm ²)	18.97 [16.37 - 21.41]	15.56 [13.96 - 19.19]	p > 0.05
Cross-section area at suture site (mm ²)	40.69 [38.89 - 48.65]	41.97 [37.20 - 49.57]	p > 0.05
FAILURE MODE :	n = 10	n = 10	
Suture breakage	0	0	p = 0.47
Knot failure	0	2 (20%)	
Suture pullout	10 (100%)	8 (80%)	