



# In vitro biomechanical comparison of three different types of single- and double-row arthroscopic rotator cuff repairs: Analysis of continuous bone-tendon contact pressure and surface during different simulated joint positions

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**Hypothesis:** We assessed bone-tendon contact surface and pressure with a continuous and reversible measurement system comparing 3 different double- and single-row techniques of cuff repair with simulation of different joint positions.

**Materials and methods:** We reproduced a medium supraspinatus tear in 24 human cadaveric shoulders. For the 12 right shoulders, single-row suture (SRS) and then double-row bridge suture (DRBS) were used. For the 12 left shoulders, DRBS and then double-row cross suture (DRCS) were used. Measurements were performed before, during, and after knot tying and then with different joint positions.

**Results:** There was a significant increase in contact surface with the DRBS technique compared with the SRS technique and with the DRCS technique compared with the SRS or DRBS technique. There was a significant increase in contact pressure with the DRBS technique and DRCS technique compared with the SRS technique but no difference between the DRBS technique and DRCS technique.

**Conclusions:** The DRCS technique seems to be superior to the DRBS and SRS techniques in terms of bone-tendon contact surface and pressure.

**Level of evidence:** Basic Science Study.

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**Keywords:** Rotator cuff; double-row repair; biomechanical study; bone-tendon contact surface; bone-tendon contact pressure

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Arthroscopic repair of rotator cuff tears is now a well-accepted technique with findings comparable to open repair in terms of clinical and tendon healing results in many studies.<sup>4,6,7,9,18-21,26,27,41,49</sup> However, numerous studies using open and arthroscopic techniques have noted the

occurrence of retears, with rates varying from 12% to 94%, which appear to be more important in patients with large or massive tears.<sup>9,11,15,18,21,22,25,27,49</sup> Hence, a few authors have proposed the use of a double-row suture (DRS) technique rather than the usual single-row suture (SRS) technique or transosseous suture (TOS) technique.<sup>3,30</sup>

Biomechanical studies comparing SRS, TOS, and DRS in terms of resistance to failure and reproduction of the natural footprint of the supraspinatus with measurement of bone-tendon contact surface and bone-tendon contact pressure are in favor of the DRS technique, showing higher loads to failure and higher bone-tendon contact pressure and surface compared with SRS or TOS techniques.<sup>2,8,12,28,31,32,34,35,38,42,46,48,51</sup>

Recent clinical studies have shown good results with DRS techniques,<sup>1,5,7,24,29,39,44,45</sup> and we are only aware of 1 comparative study, though nonrandomized, in favor of DRS techniques in terms of tendon healing.<sup>10</sup> We could find no comparative clinical study between single-row and double-row techniques showing significantly better results with one technique over the other.<sup>17,39</sup> All biomechanical studies that showed better bone-tendon contact surface and pressure for DRS techniques rely on measurement techniques that have an important limitation: the pressure-sensitive films used for measurements of contact surface and pressure do not give continuous or reversible measurements.<sup>37,46</sup> This may lead to misinterpretation of measured contact surfaces and pressures because measured data may change after knot tying and with passive shoulder movements encountered during early physiotherapy. Another limitation of some of those studies is that only 1 type of DRS technique was usually examined.

Therefore, the objectives of our biomechanical *in vitro* study were (1) to use a new bone-tendon contact surface and pressure measurement technique allowing continuous measurement before, during, and after cuff repair and during simulated shoulder movements and (2) to compare, in terms of bone-tendon contact surface and pressure, an SRS technique with a recently published technique<sup>3</sup> that will be called the double-row bridge suture (DRBS) technique and to compare 2 DRS techniques—the DRBS technique and a new technique called the double-row cross-suture technique (DRCS), which adds a cross suture to the DRBS technique.

## Material and methods

### Specimen preparation and loading simulation

We used 24 fresh-frozen cadaveric shoulders (12 left and 12 right shoulders) in 12 cadavers (5 female and 7 male cadavers; mean age, 78 years [range, 53–96 years]). All rotator cuff tendons were initially intact. All muscles but the rotator cuff muscles were removed. The distal part of the humerus was fixed in a specially designed metallic box and embedded with a low-melting point

alloy (MCP 70; Mining & Chemical Products Ltd, Wellingborough, England).

The scapula was fixed at 3 points, inferior angle, trigonum spinae, and acromial posterolateral angle, which defined the reference plane. Fixation was performed with a specially designed metallic box and MCP 70 for the inferior angle and with screws and bolts for the other points.

The humeral box was linked to a 3-dimensional system allowing all the humeral movements relative to the fixed scapula. To simulate joint anteflexion in the scapular plane, we combined elevation of the humerus in the scapular plane and external rotation around the humeral axis (Figure 1).

Four static anteflexion positions were analyzed: 30°, 60°, 90°, and 120°. For each of those static positions, the relative position of the humerus to the scapula was defined with a combination of 2 angles: elevation angle of the humerus relative to the scapula and rotational angle of the humerus relative to the scapula, according to McClure et al<sup>33</sup> and Stokdijk et al.<sup>43</sup>

Supraspinatus and infraspinatus muscle fibers were partially removed from their fossae, and the tendon of each muscle was attached to an Ethibond suture (Ethicon, Somerville, NJ) with Mason-Allen knots, with 1 suture for the supraspinatus tendon and 2 for the infraspinatus tendon.

Sutures were directed through eyelets screwed on the scapula that allowed a better simulation of muscle traction lines. The sutures were then linked through a pulley system to an Instron traction machine (Instron, Norwood, MA), simulating supraspinatus and infraspinatus muscle forces.

The traction machine progressively applied a load during experimentation up to a maximal load of 60 N. The pulley and suture system allowed us to divide this maximal load into 30 N for the supraspinatus muscle and 30 N for the infraspinatus muscle.<sup>16,42,47,50</sup>

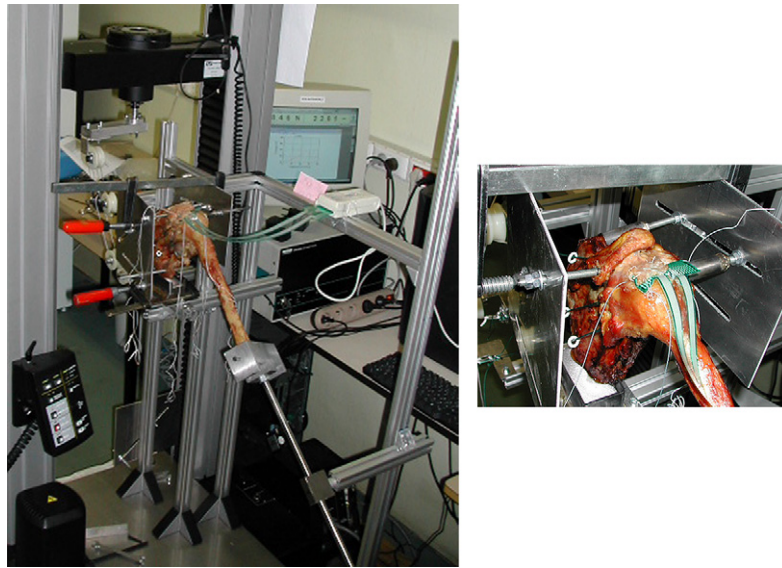
According to Van der Helm,<sup>47</sup> subscapularis muscle activity during elevation is relatively low (<10 N); we therefore decided to simulate subscapularis function only by its passive action without removing the muscle fibers from the subscapularis fossa and without adding a traction system for the subscapularis muscle.

After fixation of the experimental system in a position simulating a 30° anteflexion position, we removed 1 cm of supraspinatus tendon substance starting from the edge of the greater tuberosity and progressing medially, detaching the whole tendon from the footprint contact surface. This reproduced a supraspinatus full-thickness tear with an artificially created 1-cm tendon retraction in the frontal plane, simulating a medium tear (1 cm in the frontal plane and 2 cm in the sagittal plane).

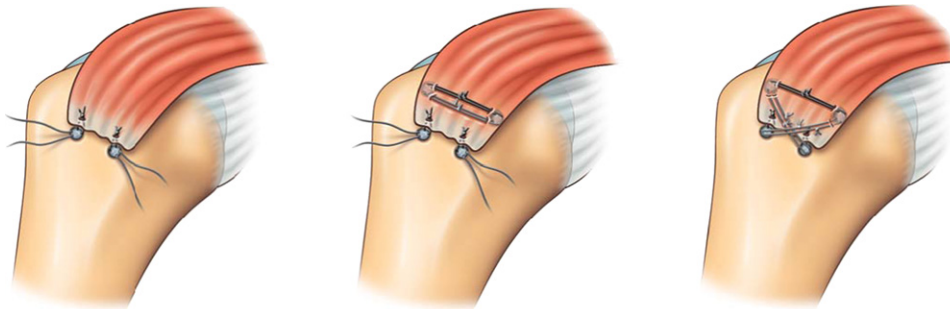
## Cuff repair and measurements

### Specific material

Cuff repair was conducted with the usual arthroscopic materials (knot pusher, cuff-penetrating graspers) and with BioZip anchors double loaded with Fiberforce sutures (Stryker, Kalamazoo, MI). For single-row anchors, we used two 6.5-mm anchors placed 2 cm below the edge of the greater tuberosity, with a 2-cm distance between the anchors. For double-row anchors, we used two 5-mm



**Figure 1** *Left*, Global view of testing setup. *Right*, Detail of contact pressure and surface measurement technique.



**Figure 2** Schema of different fixation techniques: SRS (*left*), DRBS (*middle*), and DRCS (*right*).

anchors placed just lateral to the bone-cartilage junction in alignment with the 6.5-mm lateral anchors.

For contact surface and pressure measurement, we used piezoelectric-sensitive films, with a 0- to 13.8-MPa measurement range (model 4201; Tekscan, South Boston, MA). This system allows a continuous and reversible measurement of bone-tendon contact surfaces and pressures.

After anchors insertion, the piezoelectric-sensitive film was pierced by the 8 medial sutures and the 8 lateral sutures and placed on the greater tuberosity. Care was taken not to destroy the film's sensitive cells while passing the sutures through the film.

### Suture techniques

For the SRS technique, 1 suture for each anchor was retrieved 5 mm away from the edge of the supraspinatus tendon with the usual oblique cuff-penetrating graspers. Fisherman-like sliding knots were tied, and the lateral row was hence completed.

For the DRBS technique, 2 suture rows were used: 1 lateral row as described for the SRS technique and 1 medial

row. The medial double row was created with a technique similar to that of Arrigoni et al.<sup>3</sup> The 4 sutures of each medial anchor were passed through the supraspinatus tendon 2 cm medial from its edge with oblique cuff-penetrating graspers, and the 4 posterior sutures were passed 2 cm away from the 4 anterior sutures. The first same-colored sutures were then tied, forming a double-loop "bridge-type" suture. We reproduced this double-loop suture with the other colored sutures. This completed the medial row of the DRBS technique (Figure 2).

For the DRCS technique, 2 suture rows were used: 1 lateral row identical to that used in the SRS technique and 1 medial row. After forming the first loop in a bridge-type manner, we used the remaining medial suture and placed 1 looped cross-bridge suture between the anteromedial and posterolateral anchors and 1 looped cross-bridge suture between the posteromedial and anterolateral anchors (Figure 2). This completed the DRCS technique.

Regarding experimentation for the 12 left shoulders, we first achieved the SRS technique and then prepared the sutures for the medial row of the DRBS technique but without tying the knots. Measurements were performed only for the SRS technique. Then, we tied the knots for the

medial row, and measurements were performed for the DRBS technique.

Regarding experimentation for the 12 right shoulders, we first achieved the DRBS technique with only 1 loop for the medial row, and measurements were performed. Then, we tied the loops for the DRCS technique, and measurements were performed.

## Measurement sequences

Bone-tendon footprint contact pressures and surfaces were measured in a continuous way: during knot tying, with 1 measurement being performed for each knot tied, and during traction on the supraspinatus and infraspinatus tendons for 4 static positions of glenohumeral joint ante-flexion—30°, 60°, 90°, and 120°. Measurements were stopped while moving from one position to another.

The contact pressure and surface measured at the beginning of loading (0 N) were called initial contact pressure and surface, respectively. At the end of loading (60 N), they were called final contact pressure and surface, respectively.

## Statistical analysis

Results were analyzed statistically as follows: Paired *t* tests were performed for comparison of initial contact surfaces and pressures (before traction on muscles) for each different position (30°, 60°, 90°, and 120°) between the SRS and DRBS techniques, between the DRBS and DRCS techniques, and between the SRS and DRCS techniques. Paired *t* tests were performed for comparison between initial and final contact surfaces for each different position (30°, 60°, 90°, and 120°) for the SRS technique, for the DRBS technique, and for the DRCS technique. Comparison between initial contact pressure and final contact pressure was performed for each different position (30°, 60°, 90°, and 120°) for the SRS technique (paired *t* test), for the DRBS technique (paired *t* test), and for the DRCS technique (paired *t* test for 30°, 60°, and 90° values and Wilcoxon nonparametric test for 120° values).

## Results

Qualitatively, measurements indicated different patterns with greater contact surface for the DRCS technique compared with the DRBS technique and greater contact surface for the DRBS technique compared with the SRS technique. During knot tying, contact pressure and surface variations were important and difficult to analyze because of important instantaneous variations of values (Figure 3). Mean initial contact surfaces for each position are described in Table I.

Initial contact surfaces were significantly superior with the DRBS technique compared with the SRS technique at

60°, 90°, and 120° of ante-flexion. Initial contact surfaces were significantly superior with the DRCS technique compared with the DRBS technique and with the DRCS technique compared with the SRS technique at 30° and 60° of ante-flexion.

Final contact surface was significantly superior to initial contact surface (Figure 4) at 30° and 60° of ante-flexion for the SRS technique; at 30°, 60°, 90°, and 120° of ante-flexion for the DRBS technique; and at 60° of ante-flexion for the DRCS technique.

Initial contact pressure was significantly superior for the DRBS technique compared with the SRS technique in all positions (Figure 5) and for the DRCS technique compared with the SRS technique at only 30° and 60° of ante-flexion. There was no significant difference between the DRCS and DRBS techniques in terms of initial contact pressure.

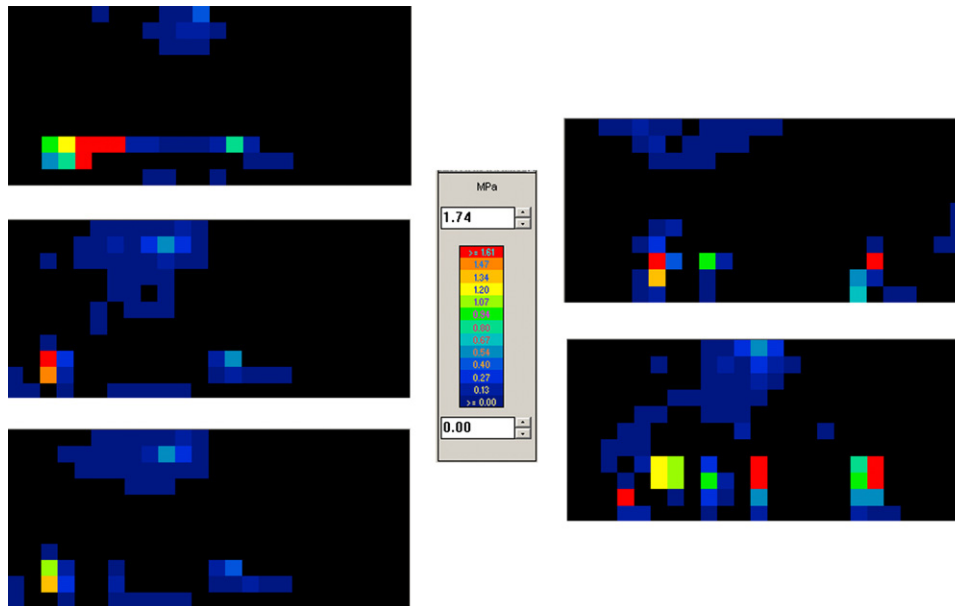
Final contact pressure was significantly superior to initial contact pressure in only 1 situation: at 120° of ante-flexion for the SRS technique.

## Discussion

Clinical and healing results of arthroscopically repaired cuffs are similar to results obtained after open repair.<sup>6,26,41</sup> However, for large to massive tears, Galatz et al<sup>18</sup> found a retear rate of 94%, and there is still controversy in the literature about residual symptoms and shoulder function after retear. Most authors have found decreasing results regarding shoulder function after retear,<sup>11,20,21,23</sup> but those inferior results may appear more than 2 years after surgery whereas patients with perfectly healed cuffs continue to have good clinical results long after 2 years.<sup>11</sup> Some retears after arthroscopic cuff surgery may be because of technical difficulties in obtaining anatomic repair of the cuff, and some authors have suggested that double-row fixation techniques have superior mechanical properties compared with single-row fixation techniques.

In recently published clinical studies evaluating clinical results of DRS techniques for rotator cuff repair, the findings tend to compare favorably with those of SRS techniques,<sup>24,29,44,45</sup> with a retear rate as low as 11.4% reported by Lafosse et al.<sup>29</sup> However, those studies were not randomized, and to our knowledge, there is no difference to date in terms of clinical results between SRS and DRS techniques in comparative studies.<sup>10,17,39</sup> In terms of load to failure and gap formation, many in vitro studies showed the superiority of variable types of DRS techniques over SRS techniques.<sup>28,31,36,38,42</sup> Because we did not use cyclic loading, we have focused on studies assessing supraspinatus footprint contact surface and pressure after different techniques of repair.

Anatomic studies of the supraspinatus insertion on the greater tuberosity show that the tendon covers the entire surface from the edge of the tuberosity to the articular



**Figure 3** Mapping of contact patterns for different situations. The map represents the surface of the sensor containing  $24 \times 11$  different sensitive cells. The non-active cells (null pressure) are in black, whereas the active cells have a color related to a calibration scale (*middle*). The total contact surface is the product of the surface of a cell ( $3.62 \text{ mm}^2$ ) by the number of active cells. *Left*, Beginning (*top*), intermediate stage (*middle*), and end (*bottom*) of knot tying with SRS technique in left shoulder of one of the tested subjects. *Right*, Comparison between DRBS technique (*top*) and DRCS technique (*bottom*) in right shoulder of same subject.

**Table I** Initial and final contact surface values (before and after loading) for different suture techniques at 4 different anteflexion positions

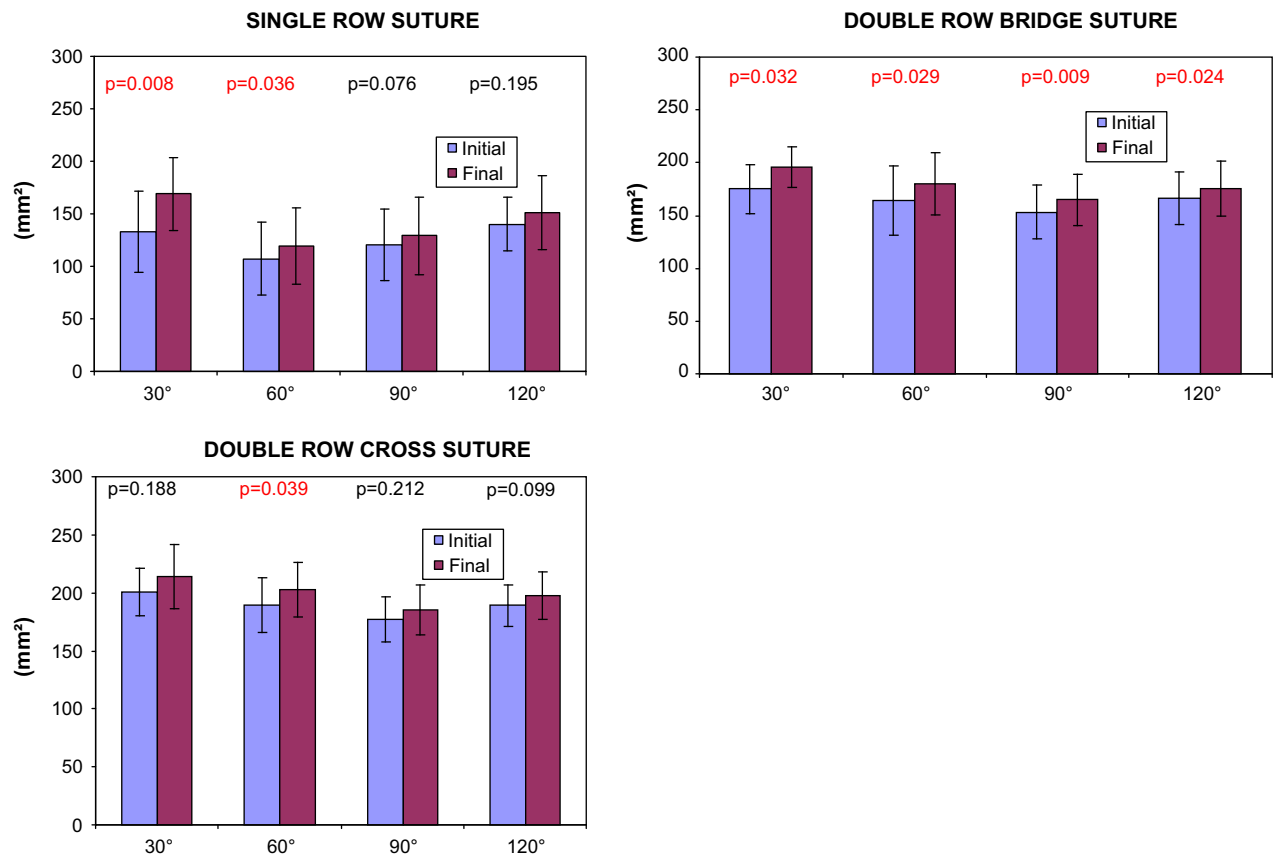
	Contact surface ( $\text{mm}^2$ )					
	SRS		DRBS		DRCS	
	Initial	Final	Initial	Final	Initial	Final
30°						
Mean	133	169	175	196	201	214
SD	39	34.5	23	19.5	20.5	28
60°						
Mean	107	119	164	180	189	203
SD	34.5	36.5	32.5	29	23.5	23.5
90°						
Mean	120	129	153	165	177	185
SD	34	37	25.5	24.5	19.5	21.5
120°						
Mean	140	151	166	176	189	198
SD	25.5	35.5	25	26	17.5	20.5

margin, representing a footprint insertion with a mean area varying from  $155 \text{ mm}^2$  to  $368 \text{ mm}^2$ .<sup>13,14,34,40</sup> We cannot compare our results with those anatomic values because we did not measure the native values in our specimens.

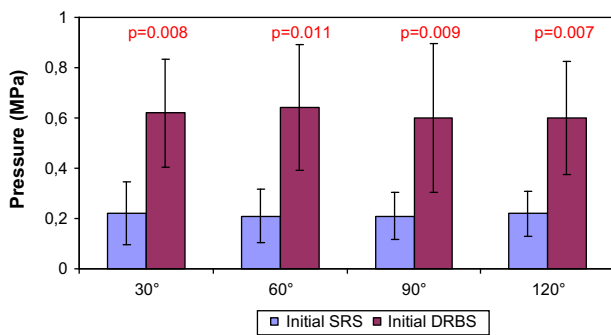
Apreleva et al<sup>2</sup> reported values ranging from  $290 \text{ mm}^2$  to  $391 \text{ mm}^2$  after 4 different SRS techniques. These values are higher than ours for the SRS technique (Table I), but their SRS techniques are not exactly the same as our SRS technique. Meier and Meier,<sup>34</sup> in a similar study, showed values ranging from  $238 \text{ mm}^2$  to  $314 \text{ mm}^2$  for a double-row mattress-type suture technique compared with values

ranging from  $155 \text{ mm}^2$  to  $242 \text{ mm}^2$  for a TOS technique and values ranging from  $79 \text{ mm}^2$  to  $199 \text{ mm}^2$  for an SRS technique. Our mean contact surface values are within the range of those of Meier and Meier for the SRS technique but are inferior to those of Meier and Meier for the DRBS technique. However, no contact pressure–sensitive film was used in these 2 studies, where the surfaces were obtained after digitization of the contour of the tendon insertion area.

Using a Fuji pressure-sensitive film technique (Fujifilm Recording Media Germany GmbH, Kleve, Germany),



**Figure 4** Initial and final contact surfaces (mean and SDs) at 4 different anteflexion positions for the different suture techniques. The *P* value is shown for each Student *t* test comparing initial and final contact surfaces.



**Figure 5** Initial contact pressure (mean and SDs) at the different anteflexion positions for the SRS and DRBS techniques. The *P* value is shown for each paired Student *t* test comparing the 2 techniques.

Tuoheti et al<sup>46</sup> reported values of 50 mm<sup>2</sup> for single-row sutures and 120 mm<sup>2</sup> for double-row mattress-type sutures. These values are lower than ours for the SRS technique, as well as for the DRS technique. An explanation could be the difference in distance between the anchors (20 mm in our study vs 10 mm in their study). Park et al<sup>37,38</sup> described a cross-type transosseous-equivalent technique that seems to be the closest to our DRCS technique. They also used Fuji pressure-sensitive films, and in their in vitro study, they found a mean value of 124 mm<sup>2</sup> for the supraspinatus footprint area

for their 4-suture bridge transosseous-equivalent technique compared with a mean value of 63 mm<sup>2</sup> for a double-row mattress-type technique and 100 mm<sup>2</sup> for a double-row bridge technique; the latter, however, appears to be quite different from our bridge technique.

Our mean surface values are higher than those of Park et al<sup>37,38</sup> for equivalent DRBS and DRCS techniques. This difference may be explained by the limitation of the size of the measurement area in their technique because of the Fuji film location within the 4 suture anchors, as well as by the different distances between the anchors (12.5 mm vs 20 mm).

Within the limits of an in vitro cadaveric study, which cannot reproduce the exact in vivo situation, we could prove that the DRCS technique was superior, in terms of bone-tendon contact surface, to the DRBS technique, which is itself superior to the SRS technique. This was not the case for all positions of the joint, but the number of cadavers may have been insufficient in terms of statistical power to prove a difference for certain joint positions.

An interesting point was the statistically significant increase in contact surface after muscle loading for the SRS and DRBS techniques but not for the DRCS technique. One could assume that the DRCS technique allows fewer micromovements of the cuff on the surface of the footprint during joint movements than the SRS and DRBS techniques. Allowing fewer micromovements of the cuff

could be better for permanent bone-tendon contact in the first weeks of physiotherapy. This could enable better bone-tendon healing assuming that permanent changes in contact between bone and tendon during joint movements may impair tendon healing.

We think that greater surface contact between bone and tendon could lead to better tendon healing, but multiple sutures on the tendon and residual high pressure after knot tying could threaten tendon vascularization and impair tendon healing.

Contact pressure values increased while passing from the SRS technique to the DRBS or DRCS technique before loading. We cannot explain the lack of difference between the DRBS and DRCS techniques apart from a statistical power explanation: the difference may be too small to be statistically significant with our small number of specimens.

To our knowledge, no data on in vivo contact pressure or data on the best bone-tendon contact pressure for optimal bone-tendon healing have been published. Values of contact pressure and surface at the end of knot tying may be closer to in vivo values in our study than in studies using Fuji pressure-sensitive films, where only the maximal values of contact pressure and surface are recorded. Indeed, important variations of contact pressures and surfaces were observed during knot tying (Figure 3). This type of variation cannot be observed with nonreversible pressure-sensitive films, which could impair results and final conclusions.

We used an open environment to place the sutures in the cuff, which is different from arthroscopic conditions with percutaneous portals and cannulas. However, knots were tied with arthroscopic knot pushers and by well-trained shoulder arthroscopic surgeons.

Finally, we did not apply cyclic loading, so our data are representative of the immediate postoperative situation, and no conclusions can be drawn regarding fatigue resistance of the suture techniques.

To our knowledge, there is no other biomechanical study in the literature comparing DRCS, DRBS, and SRS techniques with a high number of cadaveric shoulders, with continuous measurement of bone-tendon contact surface and pressure and with simulation of different joint positions.

## Conclusions

We found significantly higher contact surface values for the DRCS technique compared with the DRBS and SRS techniques and significantly higher contact pressure values for the DRCS and DRBS techniques compared with the SRS technique. We can assume, in terms of contact surface, that the DRCS technique is better than the 2 other tested techniques. Only a randomized clinical trial between the SRS and DRCS techniques would be able to show the superiority of the DRCS technique in terms of healing and clinical results.

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