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Pressure and Contact Area in Rotator Cuff Repair: A Systematic Review*

Presión y área de contacto en reparación de manguito rotador: una revisión sistemática

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Abstract

Objective To provide a comprehensive synopsis and analysis of biomechanical studies on the magnitude and distribution of pressure at the tendon-footprint interface of rotator cuff tears reported in the literature in the last five years.
Methods The research was performed according to the methods described in the Cochrane Manual. The results are reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) consensus. The search was performed on June 1st, 2020. We identified and included ex vivo basic science studies and published biomechanical studies that evaluated the magnitude and distribution of pressure at the tendon-footprint interface of rotator cuff tears repaired between January 2015 and June 2020. Systematic searches on the MEDLINE, Embase, Scopus and Google Scholar databases were performed using the terms and Boolean operators: (*Rotator Cuff* OR *Supraspinatus* OR *Infraspinatus* OR *Subscapularis* OR *Teres Minor*) AND *Pressure* AND *Footprint*. In the Embase database, respecting its syntax, the following was used: *Rotator Cuff* AND *Pressure* AND *Footprint*.
Results In total, 15 of the 87 articles found fulfilled all the eligibility criteria and were included in the analysis.
Conclusion The pressure and contact area would be biomechanically optimized with an equivalent transosseous double-row repair, without knots in the medial row, and

Keywords
- rotator cuff
- pressure
- suture
- suture techniques
- tendon injuries
- tendons

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with the use of tapes for its execution, specific repair concepts for delaminated tears, and a limitation of abduction in the immediate postoperative period.

Resumen

Objetivo Proporcionar una sinopsis exhaustiva y un análisis de los estudios biomecánicos sobre la magnitud y distribución de la presión en la interfase tendón-huella de las roturas del manguito rotador, informadas en la literatura en los últimos cinco años.
Métodos La investigación se realizó de acuerdo con los métodos descritos en el Manual Cochrane. Los resultados se informan de acuerdo con el consenso de Ítems Preferidos de Reporte en Revisiones Sistemáticas y Metaanálisis (Preferred Reporting Items for Systematic Reviews and Meta-Analyses, PRISMA, en inglés). La búsqueda se realizó el 1^er^ de junio de 2020. Se identificaron e incluyeron estudios *ex vivo* de ciencia básica y estudios biomecánicos publicados, que evaluaran la magnitud y distribución de la presión en la interfase tendón-huella de las roturas del manguito rotador reparadas entre enero de 2015 y junio de 2020. Se realizaron búsquedas sistemáticas en las bases de datos MEDLINE, Embase, Scopus y Google Scholar utilizando los términos y operadores booleanos: (*Rotator Cuff* OR *Supraspinatus* OR *Infraspinatus* OR *Subscapularis* OR *Teres Minor*) AND *Pressure* AND *Footprint*. En la base de datos Embase, respetando su sintaxis, se utilizó: *Rotator Cuff* AND *Pressure* AND *Footprint*.
Resultados Un total de 15 de los 87 artículos encontrados cumplieron con todos los criterios de elegibilidad y se incluyeron en el análisis.
Conclusión La presión y área de contacto sería optimizada biomecánicamente con una reparación transósea de doble fila equivalente, sin nudos en la hilera medial, y con el uso de cintas para su ejecución, conceptos de reparación específica para roturas delaminadas, y limitación de la abducción en el postoperatorio inmediato.

Palabras Claves
- manguito de los rotadores
- presión
- sutura
- técnicas de sutura
- traumatismos de los tendones
- tendones

Introduction

The arthroscopic repair of the rotator cuff has been increasing constantly in recent times.[1] In most cases, the clinical and functional outcomes are good to excellent both in the short and long terms;[2–5] however, the rates of rerupture are still considerable, ranging from 11% to 68% in some series, even reaching 94% in selected reports.[6–8]

The surgery for rotator cuff repair seeks to establish a fibrovascular interface between the tendon and the footprint, which is required for the healing and restoration of the fibrocartilaginous attachment (enthesis); to do so, the construct must maximize the pressurized contact between tendon and bone while maintaining the mechanical resistance against a physiological load.[9] Rerupture is associated with patient- and repair-related (anatomical) factors. The patient-related factors include increasing age, greater tear size (with involvement of multiple tendons), lower tendon quality, muscle atrophy, fat degeneration (Goutallier classification of 3 or more), tendon retraction, longer evolution, and comorbidities (smoking, diabetes, hypercholesterolemia, alcoholism, obesity, and hypertension).[7,10]

The anatomical factors of the repair include construct tension, tissue perfusion, micromotion at the tendon-footprint interface, and footprint contact area and pressure.[11] The underlying principle is that a greater magnitude and distribution of the tendon-to-bone contact area will result in a greater chance of tendon healing.[12]

Several biomechanical studies of double-row (DR) repairs have shown an increased resistance to load-related failure and a decreased gap formation at the tendon-footprint interface compared to single-row (SR) repairs.[5,13]

The transosseous-equivalent (TOE; also called suture bridge) technique was designed to improve the magnitude and distribution of pressure at the footprint from repaired rotator cuff tears; the ends of the medial row suture are placed over the bursal side of the rotator cuff and secured to the lateral margin of the footprint with a knotless anchor.[14,15]

The present systematic review aims to provide an exhaustive synopsis and critical analysis of the biomechanical studies on the magnitude and distribution of pressure at the tendon-footprint interface of rotator cuff tears, considering several repair factors reported in the literature during the last five years.

Materials and Methods

The research was conducted according to the methods described in the Cochrane Handbook.[16] Results are reported per the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) consensus.[17] The query was conducted on June 1st, 2020

Eligibility Criteria

Published ex vivo basic science and biomechanical studies evaluating the magnitude and distribution of pressure at the tendon-footprint interface of rotator cuff tears repaired from January 2015 to June 2020 were identified and included if they met the following criteria: measurement of the contact area and pressure at the tendon-footprint interface, and complete description of the configuration of the biomechanical tests, of the surgical techniques, and of the methodology used.

Clinical outcome studies, research theses, conference abstracts, articles on surgical techniques, and book chapters were excluded.

Bibliographic Search

A systematic review of the literature was conducted to identify all publications in English on the biomechanical evaluation of rotator cuff repairs. Systematic queries were carried out in the MEDLINE, Embase, Scopus and Google Scholar databases using the following terms and Boolean operators: (*Rotator Cuff* OR *Supraspinatus* OR *Infraspinatus* OR *Subscapularis* OR *Teres Minor*) AND *Pressure* AND *Footprint*. For the Embase database, respecting its syntax, the following terms were used: *Rotator Cuff* AND *Pressure* AND *Footprint*. Four reviewers independently selected papers based on titles and abstracts. All eligible articles were manually referenced to ensure the potential inclusion of other studies. Disagreements were solved consensually. The query was conducted on June 1st, 2020.

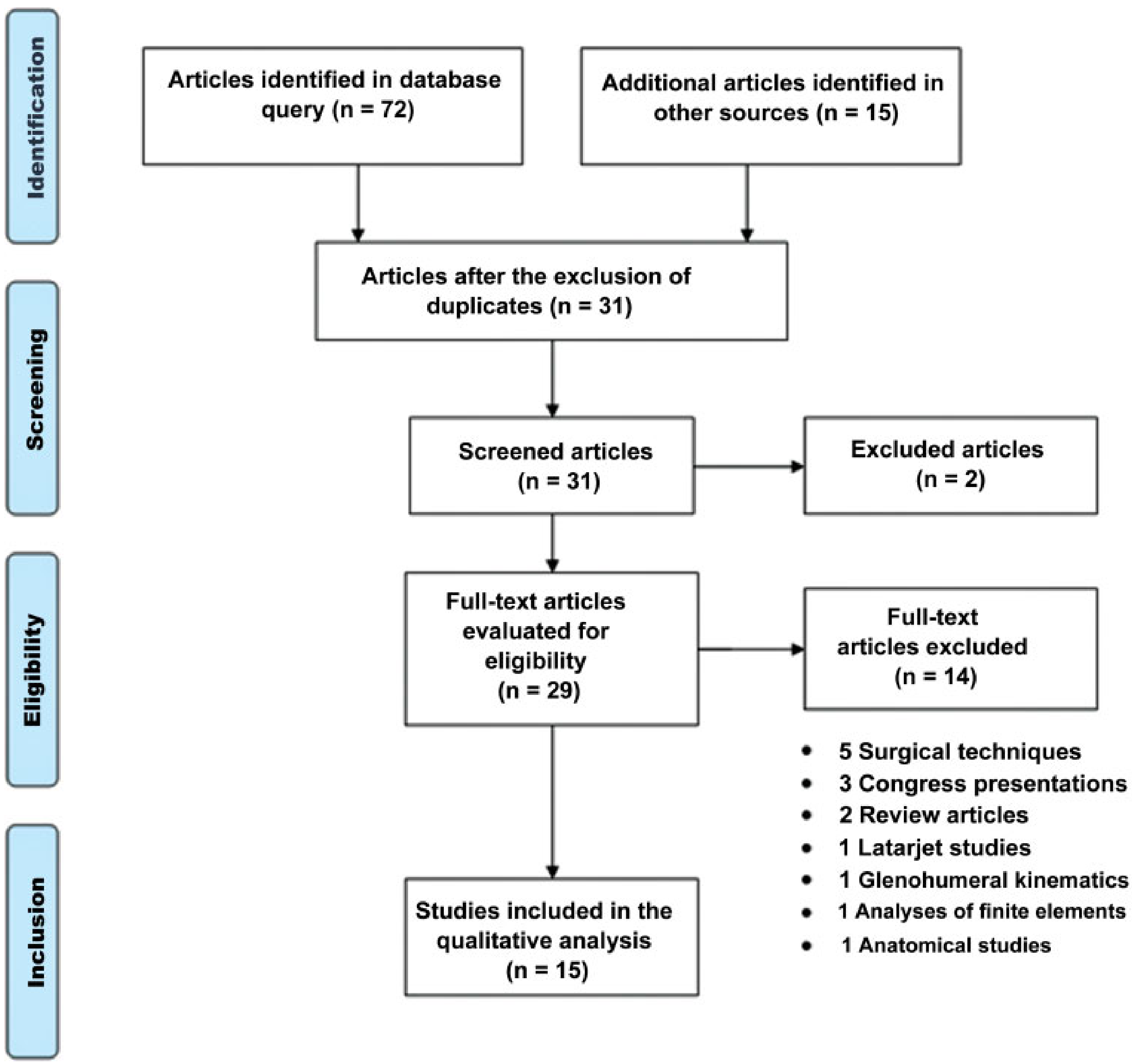

Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart. From the 87 initial papers, 15 studies were included.

Table 1 Biomechanical evaluations from the papers included in this systematic review

Authors	N	Model	Biomechanical Evaluation
Caldow et al.[18]	56	Lamb	Evaluation of pressure distribution with Fujifilm (Super-low)
			Repair tension, 10 N
			Determination of the load at failure
Dyrna et al.[19]	30	Human	Humeral position: 0° of rotation and 0° of abduction
			Preload, 10–100N; 300 cycles at 0.5 Hz
			Contact area, contact force, contact pressure, peak in contact pressure, and failure mode were measured
Huntington et al.[20]	60	Lamb	Evaluation of pressure distribution with Fujifilm (Super-low)
			Preload, 10 N. Evaluation of repair pressure evaluation was performed with Dynacell Instron load cell
			200 cycles, 10–62N at 0.25 Hz
			Footprint contact pressure, contact area, stiffness, tensile strength, failure mode
Kim et al.[21]	22	Human	Evaluation of pressure distribution with Fujifilm for 120 seconds after the repair
			Repair tension, 40 N
Liu et al.[22]	16	Ovine	Humeral position: -10°, 0°, and 10° of abduction
			Preload, 30 N
			The footprint contact pressure was measured at 10 N, 20 N and 30 N
			Measurement with Dynacell Instron load cell
			Determination of the load at failure
Liu et al.[23]	10	Ovine	Humeral position: 0°, 20°, and 40° of abduction
			Self-reinforcement was measured with progressive loads from 10 to 60 N
			Measurement with Dynacell Instron load cell
			Footprint contact pressure, yield load, tensile load at failure, and maximum energy at failure
Ng et al.[24]	24	Porcine	Evaluation of pressure distribution with Fujifilm (Prescale Ultra Super Low Pressure) for 60 seconds after the repair
			Repair stress was not measured
Park et al.[25]	18	Human	Humeral position: 30° of external rotation, 0° of rotation, 30° of internal rotation; 0° and 30° of abduction
			Contact force, area, and pressure measured with Tekscan 4041, load at failure
			Tensiometry at 60 N, 90 N, and 120 N (transosseous-equivalent suture)
			Tendon load at 30 N
Park et al.[26]	8	Human	Humeral position: 0° and 30° of abduction
			Contact force, area and pressure measured with Tekscan 4041
			Self-reinforcement was measured with progressive loads from 0 to 60 N
Pauzenberger et al.[27]	18	Human	Humeral position: 30°-60° of external rotation, 0° of rotation, 30°-60° of internal rotation; 0°, 30°, and 60° of abduction
			Preload, 30–50 N. Assessment of repair pressure with Tekscan Model 4205 sensor
			200 cycles, 10–100 N at 1 Hz
			Contact area, contact pressure, and failure mode were measured
Simmer Filho et al.[28]	24	Human	Humeral position: 0° of rotation and 0° and 30° of abduction
			Preload, 30 N. Assessment of repair pressure with Tekscan Model 4205 sensor
			50 N for 30 seconds to 30 N for 30 seconds
			Contact area and contact pressure were measured
Smith et al.[29]	18	Ovine	Humeral position: -10°, 0°, 10°, 20°, 30°, 40°, 50° and 60° of abduction

(*Continued*)

Table 1 (*Continued*)

Authors	N	Model	Biomechanical Evaluation
			Self-reinforcement was measured with progressive loads from 10 N to 60 N
			Measurement with Dynacell Instron load cell
			Footprint contact pressure
Smith et al.[30]	18	Ovine	Humeral position: 0° and 20° of abduction
			Self-reinforcement was measured with progressive loads from 10 N to 60 N
			Measurement with Dynacell Instron load cell
			Footprint contact pressure, yield load, tensile load at failure, and maximum energy at failure
Stone et al.[31]	60	Sawbone	Humeral position: 0° of rotation and 0° of abduction
			Contact area and contact pressure were measured with Tekscan (model not specified)
Urch et al.[32]	10	Human	Humeral position: 30° of external rotation, 0° of rotation, 30° of internal rotation; 0° and 30° of abduction
			Preload, 25 N. Assessment of repair pressure with Tekscan model 4040 sensor
			Contact area, contact force, contact pressure, and peak in contact pressure were measured

Results

Study Selection and Features

In the literature search, we identified 31 studies for consideration; based on the abstracts, two were excluded because they were book chapters. Another 14 studies were excluded after a review of the full texts, and only 15 articles met all the eligibility criteria and were included for analysis (►**Figure 1**).[18–32] Overall, inter-reviewer agreement regarding the final eligibility was excellent (there were no disagreements). These 15 studies were published in English from 2015 to 2020. The main features of the studies are summarized in ►**Table 1**. The articles were grouped per relevant topics: "Biomechanics of the medial row in double row repairs," "Comparison of tape versus suture," and "Biomechanical characteristics of different configurations."

Biomechanics of the Medial Row in Double Row Repairs

It is believed that preserving the structural integrity of the rotator cuff by avoiding knots in damaged tissues would improve healing.[33,34] Stone et al.[31] measured the contact force and pressure at the tendon-footprint interface in a Sawbone (Vashon Island, WA, US) model graduated for biomechanical studies using an acellular human dermis allograft to simulate the rotator cuff tendon. The authors[31] compared a DR construct with a medial row with no knots to a medial row with knots, and found no significant differences. Qualitatively, they described that knotting the medial row increased the focal contact pressure and corrugated the periphery of the construct; however, this phenomenon was not evaluated quantitatively, and its biological impact was not assessed. These results support the hypothesis that a knotless medial row does not reduce the total contact force in a DR construct, which would favor biological factors for repair from a theoretical point of view.

However, this biomechanical equivalence could be altered in a suture bridge DR technique. Since the knots in the medial row create a tenodesis effect after being tied, an increased load (by traction of the rotator cuff) would not cause a wedge effect at the suture material; as such, the tendon would not fit in the footprint bone, and these positive effects would be lost.[35]

Smith et al.[30] evaluated this wedge and self-reinforcement effects by comparing the contact pressure at the tendon-footprint interface generated under progressive stress loads between two suture bridge repair techniques (with or without knots at the medial row). Their findings confirm that self-reinforcement occurs in rotator cuff repairs with a DR suture bridge with or without medial row knots; the performance load approached the final failure load, and the rate of progression of the footprint compression was higher in the knotless group. This provides biomechanical evidence that the self-reinforcement mechanism is decreased by medial row knots, probably associated with a tenodesis effect. Therefore, a suture bridge repair without medial knots presents the same characteristics of biomechanical resistance, but improved magnitude and distribution of pressure at the tendon-footprint interface, associated with less folding of the tendon and a theoretical

Table 2 Repair configurations from included papers

Authors	Repair configuration
Caldow et al.[18]	SR1: Single-row crossed suture with overlapping sutures oriented at 45° to the tendon, 2 TwinFix anchors loaded with FiberWire # 2
	SR2: Single-row Mason-Allen suture, 2 TwinFix anchors loaded with FiberWire # 2
	DR1: 2 medial mattress sutures and 2 lateral Mason-Allen sutures, 4 TwinFix anchors loaded with FiberWire # 2
	Transosseous repair with Fiberwire # 2
Dyrna et al.[19]	25% superior subscapularis tear
	SR: 2 × 4.5-mm, double loaded Bio-Corkscrew
	Hybrid DR: 2 × 4.75-mm Bio-Swivelock (1 superior-lateral anchor and 1 inferior-medial anchor; 1 FiberTape loop)
	25% superior subscapularis tear
	SR: 2 × 4.5-mm, double loaded Bio-Corkscrew
	Hybrid DR: 2 × 4.75-mm Bio-Swivelock (1 superior-lateral anchor and 1 inferior-medial anchor; 1 FiberTape loop)
	DR: 3 × 4.75-mm Bio-Swivelock (1 superior-lateral anchor and 2 medial anchors; 2 FiberTape loops)
Huntington et al.[20]	DR1: Suture bridge with FiberWire # 2 and 4 Bio-Swivelock knotless anchors
	DR2: Suture bridge with FiberTape and 4 Bio-Swivelock knotless anchors
	DF3: Suture bridge with FiberWire # 2 and 3 Bio-Swivelock knotless anchors
	DF4: Suture bridge with FiberTape and 3 Bio-Swivelock knotless anchors
Kim et al.[21]	TOE1: 2 × 5.0-mm medial Paladin, single load of Hi-Fi # 2 (knotted row) + 2 x lateral PopLok, no knotless
	TOE1: 2 × 5.0-mm medial Paladin, single load of Hi-Fi # 2 (modified Mason-Allen) + 2 x lateral PopLok, knotless
Liu et al.[22]	TB1: Tension band with 2 FiberWire inverted mattress sutures and 2 lateral 5.5-mm SwiveLock anchors with no knot
	TB2: Tension band with 2 FiberTape inverted mattress sutures and 2 lateral 5.5-mm SwiveLock anchors with no knot
Liu et al.[23]	DR1: 2 × 4.75-mm medial SwiveLock, single load of FiberWire # 2 (knotted row) + 2 × 4.75-mm lateral Bio-Swivelock, no knot
	DR2: 2 × 4.75-mm medial SwiveLock, single FiberTape load (knotless row) + 2 × 4.75-mm lateral Bio-Swivelock, with no knot
Ng et al.[24]	DR1: 2 × 5.5-mm medial Bio-Corkscrew, double load of FiberWire # 2 + 2 × 5.5-mm lateral Bio-Swivelock, no knot
	DR2: 2 × 5.5-mm medial Bio-Corkscrew, double load of FiberWire # 2 + 1 × 5.5-mm lateral Bio-Swivelock, no knot
	DR3: 1 × 5.5-mm medial Bio-Corkscrew, double load of FiberWire # 2 + 2 × 5.5-mm lateral Bio-Swivelock, no knot
Park et al.[25]	TOE: 2 × 5.5-mm medial Healix, single load of FiberWire # 2 (knotless row) + 2 x lateral Corkscrew (with suture passer)
Park et al.[26]	TOE1: 2 × 5.5-mm medial SwiveLock, single load of FiberTape (knotted row) + 2 × 4.75/5.5-mm lateral Bio-Swivelock, no knot
	TOE2: 2 × 5.5-mm medial SwiveLock, single load of FiberTape (knotless row) + 2 × 4.75/5.5-mm lateral Bio-Swivelock, no knot
Pauzenberger et al.[27]	TOE, medially knotted bridge: 2 × 5.5-mm medial Bio-Corkscrew, double load of FiberWire # 2 (medial to the cable, knotted) + 2 × 5.5-mm lateral Bio-Swivelock, no knot
	TOE, knotless bridge: 2 × 5.5-mm medial Bio-Swivelock, single load of FiberTape + 2 × 5.5-mm lateral Bio-Swivelock, no knot
	TOE, double-layer: 2 × 5.5-mm medial Bio-Corkscrew, double load of FiberWire # 2 (medial to the cable, 1 suture and 1 articular loop suture) + 2 × 5.5-mm lateral Bio-Swivelock, no knot
Simmer Filho et al.[28]	SR1: 2 × 4.5-mm Bio-Corkscrew FT, double load of FiberWire # 2 (single knots)

(*Continued*)

Table 2 (*Continued*)

Authors	Repair configuration
	SR2: Tension band with 2 FiberTape inverted mattress sutures and 2 4.75-mm Bio-Composite SwiveLock anchors
	SR3: Tension band with 2 FiberTape inverted mattress sutures + FiberLink medial to the mattress sutures with 2 4.75-mm Bio-Composite SwiveLock anchors
Smith et al.[29]	DR1: 2 × 4.75-mm medial SwiveLock, single load of FiberWire # 2 (knotted row) + 2 × 4.75-mm lateral Bio-Swivelock, no knot
	DR2: 2 × 4.75-mm medial SwiveLock, single load of FiberWire # 2 (knotless row) + 2 × 4.75-mm lateral Bio-Swivelock, no knot
Smith et al.[30]	DR1: 2 × 4.75-mm medial SwiveLock, single load of FiberWire # 2 (knotted row) + 2 × 4.75-mm lateral Bio-Swivelock, no knot
	DR2: 2 × 4.75-mm medial SwiveLock, single load of FiberWire # 2 (knotless row) + 2 × 4.75-mm lateral Bio-Swivelock, no knot
Stone et al.[31]	DR1: 2 × 5.5-mm medial PEEK Healicoil, double load of FiberWire # 2 (with knots) + TO lateral row + matrix HD acellular human dermis allograft
	DR2: 2 × 5.5-mm medial PEEK Healicoil, double load of FiberWire # 2 (no knot) + TO lateral row + matrix HD acellular human dermis allograft
	DR3: 2 × 5.5-mm medial PEEK Healicoil, double load of FiberTape and suture (with knots) + TO lateral row + matrix HD acellular human dermis allograft
	DR4: 2 × 5.5-mm medial PEEK Healicoil, double load of FiberTape and suture (no knots) + TO lateral row + matrix HD acellular human dermis allograft
Urch et al.[32]	Classic TOE: 2 × 5.5-mm medial anchor, double load of FiberWire # 2 + 2 × 4.75-mm lateral suture, no knot
	Augmented TOE with lateral edge fixation: 2 × 5.5-mm medial anchor, double load of FiberWire # 2 + 2 × 4.75-mm lateral, no knot suture + 2 lateral edge loop sutures

Abbreviations: TB, tension band; DR, double row; SR, single row; TO, transosseous; TOE, transosseous-equivalent; PEEK, polyether ether ketone; HD, human dermis.

better tissue irrigation, potentially favoring the healing of the rotator cuff in all aspects.

In 2018, Smith and Lam[29] used a very similar biomechanical model, but focused on the effect of shoulder abduction at -10°, 0°, 10°, 20°, 30°, 40°, 50° and 60°. They found out that contact pressures at the tendon-footprint interface and self-reinforcement are greater at lower abduction angles both for knotted and knotless techniques. This has implications for rehabilitation after rotator cuff repair using a DR suture.

Park et al.[26] measured the effect of medial row knots on self-reinforcement and footprint contact. The test variables included humeral abduction at 0° and 30°. This study[30] demonstrated that medial row knots inhibited self-reinforcement; in particular, the medial knots did not improve footprint contact. Such knots effectively cause tenodesis of the repair, preventing the lateral tendon from self-reinforcing and concentrating stress on the medial row; tendon loading is not easily transmitted, and it does not become a compressive force on the repaired footprint. This could provide a biomechanical rationale for medial failures.

The TOE repair results in a higher healing rate at the tendon-footprint interface compared to the SR repair;[5,13] however, TOE repair is associated with a unique rerupture pattern. Many failures occurred at the medial row with a well-attached tendon in the greater tuberosity despite satisfactory healing at the repair site.[26] Possible over-tension and strangulation at the knotted medial row can leave the repaired tendon vulnerable to rerupture.[26]

Tension is an important factor to consider to not decrease tendon tissue perfusion, which has negative consequences for healing.[36,37] In a TOE repair model with variable and measured tension, Park et al.[25] demonstrated how an increased tension at bridge suture from 60 N to 120 N generated a significant increase in contact force, maximum pressure, and mean pressure at the tendon-footprint interface in all positions. However, regarding the contact area, although there were significant differences between 60 N and 90 N, except for one position (30° of abduction and 30° of external rotation), no significant differences were observed between 90 N and 120 N. Therefore, data suggest that tensioning a bridge suture over 90 N has no apparent benefit in this cadaveric model at

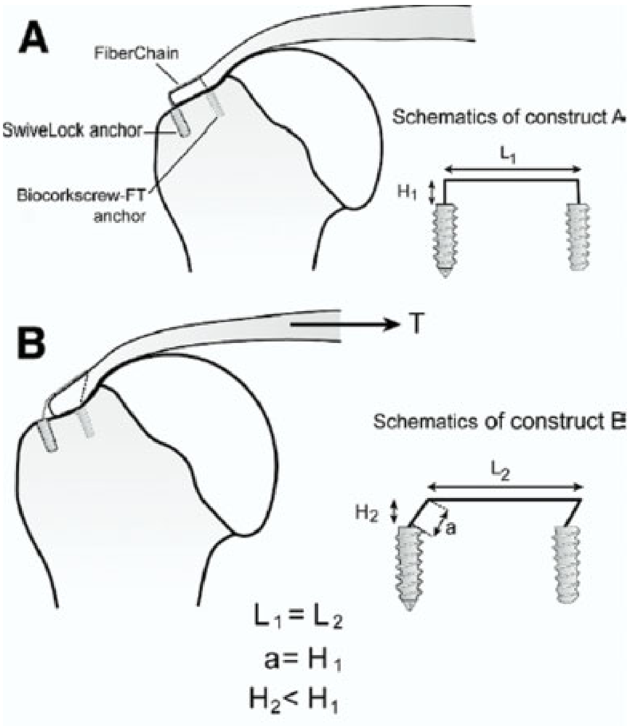

Fig. 2 (**A**) Schematic representation of a double row SwiveLock and FiberChain (Arthrex) repair configuration prior to load application (abbreviations: H1, rotator cuff thickness before loading; L1, tendon length under FiberChain). (**B**) Schematic representation of a repair configuration after loading (abbreviations: T, tensile load force; L2, tendon length under FiberChain; a, length of FiberChain between the tendon edge and the lateral anchor; H2, compressed rotator cuff thickness under tensile load). Reproduced with permission from Burkhart et al.[35]

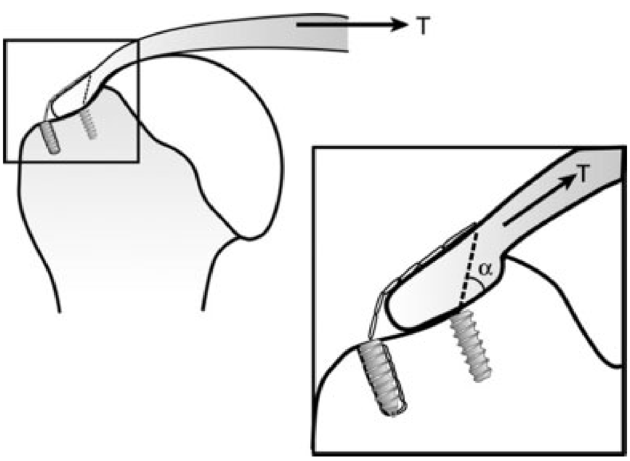

Fig. 3 After tendon loading: FiberChain (Arthex) wedge effect on the tendon. As the load (T) increases, the angle (α) mdecreases, wedging the tendon more firmly between the FiberChain and the bone. Reproduced with permission from Burkhart et al.[35]

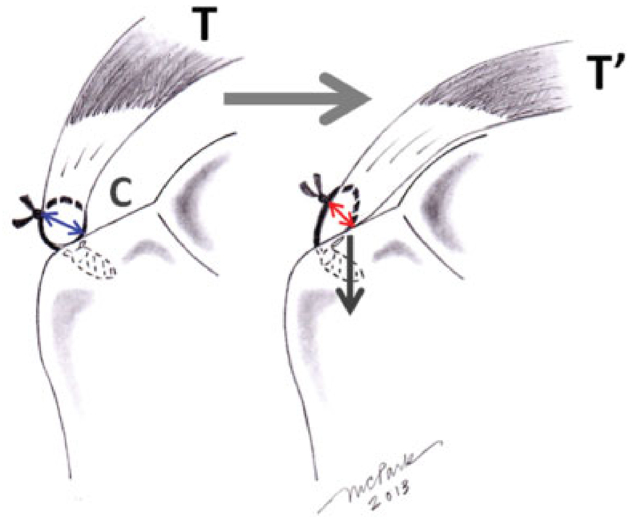

Fig. 4 The schematic representation shows how footprint contact increases with a higher tendon load. As tendon loading increases from T to T', the suture loop of a non-medially fixed repair lengthens and narrows (double arrows), creating a focal loop wedge effect. This effect creates a compression vector on the footprint laterally, reducing the exposed contact area (C). With medial fixation and tendon bridge sutures, the wedge effect can include the entire medial footprint. Reproduced with permission from Park et al.[48]

time zero, which correlates with unnecessary overtension in some constructs.

Kim et al.[21] evaluated whether the medial knotless TOE repair using a modified Mason-Allen configuration would provide a tendon-footprint interface contact area and pressure comparable to the one resulting from the conventional TOE repair with medial knots. The conventional TOE repair showed significantly greater contact area and interface pressure than the TOE repair with no medial knots based on a measurement with a pressure-sensitive film. Although these findings are probably associated with the type of measurement, one must bear in mind that the Mason-Allen technique would not add more benefit compared to the knotless repair.

In this sense, evaluating self-reinforcement with no knots, Simmer Filho et al.[28] compared two variations of SR knotless repairs (knotless repair and knotless rip-stop repair) with an SR repair with knots in terms of contact pressure and area. The most important findings were that, under tension loading, both SR knotless techniques showed better footprint coverage and a larger contact area compared to SR suture with knots. In addition, both knotless techniques resulted in more uniform pressure distribution patterns.

Comparison of Tape versus Suture

Tape is a typically flat, braided suture material used primarily in knotless repairs. Thanks to its larger width, it may reduce the incidence of suture tendon pull compared to traditional suture, while increasing construct strength at the footprint.[38] De Carli et al.[39] were among the first to propose a biomechanical study demonstrating a greater construct stability.

The first study to examine the biomechanical and clinical outcomes of a rotator cuff repair with thicker tape was conducted by Liu et al.[22] i0n 2017. For the biomechanical part of this study, they compared the effect on contact pressure at the tendon-footprint interface of two tension band constructs, only replacing FiberWire (Arthrex, Naples, FL, US) with FiberTape (Arthrex). The rotator cuff repair with tape showed a three-fold footprint contact pressure compared to that of the suture repair (0° rotation under a 30-N load). The final load at failure for the tape repair group was significantly higher (1.5-fold) compared to that of the suture group.

Huntington et al.[20] compared the contact pressure, area, and mechanical strength obtained with suture and tape. Tape repair constructs presented higher tensile strength. However, the maximum tensile strength was higher using tape only in four-anchor constructs (compared to three-anchor constructs). Stiffness was not significantly different between tape and suture in both repair groups.

Liu et al.[23] evaluated self-reinforcement biomechanically by comparing repairs performed with different suture materials. Progressive increases in contact pressure were observed for both materials as stress increased. Self-reinforcement was higher in knotless FiberTape repair (higher increase in footprint compression). Despite an improved performance load for the FiberTape group, the difference between performance load and final load was similar for both techniques. Furthermore, the results this study[23] confirm that shoulder abduction reduces self-reinforcement for both constructs, although this effect was less marked in the FiberTape group.

Biomechanical characteristics of different configurations

While many studies assessed the biomechanical properties and outcomes from SR or DR repairs, few[24] have compared different DR configurations, particularly regarding the contact area at the tendon-footprint interface.

Using an infraspinatus tendon from a porcine model, Ng and Tan[24] compared pressure distribution in three DR configurations (suture bridge; two medial anchors and one lateral anchor; and one medial anchor and two lateral anchors). These authors showed that this technique results in a good contact area at the footprint (> 70% of compression), and that the use of a three-anchor configuration compared to four anchors produces a similar footprint contact area in medium tears (no greater than 1.5 cm × 2.5 cm).

It is important to consider the formation of gaps at the anterior edge of the TOE repair with humeral rotation.[40] Internal and external rotations have different effects on tension at the anterior and posterior regions of the repair.[32]

Urch et al.[32] evaluated contact pressures by adding two suture loops to the free lateral edge of the tendon and including them in the anchor with no lateral knot (luggage-tag configuration). These authors demonstrated higher pressures (mean difference = 23.1 kPa) compared to those of the classic TOE construct. In addition, the luggage-tag configuration presented significantly higher contact pressures at 30° of internal rotation and 30° of external rotation at 0° and 30° abduction. The contact area presented no statistically significant differences in any of the test conditions.

The upper portion of the subscapularis tendon gained biomechanical relevance recently.[19,41] Yoo et al.[42] investigated the subscapularis tendon in detail and highlighted the importance of its superior lateral edge; since it commonly represents the initial rupture site with inferior progression, these authors introduced the term "leading edge". Dyrna et al.[19] analyzed three repair configurations (SR with two anchors; hybrid DR with one superior-lateral anchor; and DR with two medial anchors and one superior-lateral anchor) in a 25% and 50% superior subscapular rupture model. Footprint coverage presented no significant differences regarding defect size. As for coverage and reconstruction of the leading edge of the subscapularis, significant differences were observed between the SR construct and the construct with a superior-lateral anchor in favor of the latter, regardless of the tear size and the number of anchors used.

Delamination is described as a horizontal tear between rotator cuff layers, and it results in local ischemia, synovial-like lining, increased movement between layers, tear progression, and altered biomechanics.[43] The prevalence of delamination in extensive rotator cuff tears has ranged from 38% to 88% in the literature;[44] in addition, delamination has been identified as a negative prognostic factor for rotator cuff repairs.[45]

However, common DR repair techniques ignore the multilayer structure of the rotator cuff and fail to restore the superior joint capsule and tendon attachment. Such non-anatomical reconstruction can result in tendon tension mismatch, unfavorable changes in the biomechanics of the glenohumeral joint, and eventual repair failure.[27] Pauzenberger et al.[27] compared widely-used "en masse" DR rotator cuff repair configurations (TOE with FiberWire and TOE with FiberTape) and a specific double-layer repair technique that provided a larger contact area and an improved footprint restoration at 60° of glenohumeral abduction; furthermore, its displacement under cyclic loading was similar to that of the native tendon. The maximum load at failure was comparable between repair constructs. Therefore, it is likely that these "en masse" traditional repairs do not provide actual anatomical restoration of the rotator cuff and capsule attachment or native stress conditions. These findings suggest that specific knotless DR repairs could anatomically restore the static restraint provided by the superior joint capsule and the dynamic appearance of the rotator cuff facilitated by the tendon layer at the bursal side, combining benefits from knotless repairs with the fixation force of a TOE repair with medial knots.[27]

The Mason-Allen repair has higher tensile strength compared to that of plain and mattress repairs; the final strength of a DR repair is significantly higher.[46,47]

Caldow et al.[18] evaluated the contact area, contact pressure, tensile strength, and stiffness of a new SR crossed suture repair, and compared them to three widely-used techniques (Mason-Allen, TOE and DR suture). The crossed suture repair consists of two overlapping sutures oriented at 45° to the tendon, increasing tendon-footprint contact and preventing tendon slippage.

The most significant finding of this study[18] was that this new SR crossed suture repair technique improved pressurized contact area compared to the Mason-Allen repair and results in mean contact pressures similar to the Mason-Allen and DR techniques. The study by Caldow et al.[18] showed that the crossed suture repair produced a 66% greater footprint contact area compared to that of the Mason-Allen repair and a final tensile strength similar to that of the Mason-Allen repair. The DR repair had significantly higher maximum tensile strength than that of the crossed suture, Mason-Allen, and TOE repairs.

Discussion

The surgery for rotator cuff repair seeks to establish a fibrovascular interface between the tendon and the footprint, which is required for healing.[9] Rerupture is influenced by patient- and repair-related factors, while contact area and pressure at the tendon-footprint interface rely on the surgical technique chosen and its execution by the surgeon.

Several biomechanical studies[5,13] on the DR repair showed an increased resistance to load-related failure, improved contact areas and pressure, and decreased gap formation at the tendon-footprint interface when compared with SR repairs. However, the various configurations of the DR repair analyzed in this review have a direct impact on contact area and pressure at the tendon-footprint interface.

Self-reinforcement is a mechanism described by Burkhart et al.[35] in 2009, in which increased stress applied to the construct augments resistance to structural failure due to a progressive increase in the compression forces at the tendon footprint. The compressive forces created at the footprint increase the resistance to friction between tendon and bone, thus reducing the formation of gaps between these two surfaces.[29,30,35]

Three biomechanical mechanisms have been proposed to explain self-reinforcement in rotator cuff repairs.[35] Two of them are based on narrowing or wedging of the angle between the suture material and the bone as the tendon progressively tightens. In the suture bridge repair, the shape of the bridge suture construct (viewed at the coronal plane, ►**Fig. 2a**) changes from rectangular to trapezoidal as the tensile load increases.[35] This causes an elastic deformation of the tendon, creating a compressive force perpendicular to the bone surface, which increases with the tensile load (►**Fig. 2b**).[29,30,35]

A second mechanism in DR suture bridge repairs is the narrowing or wedging of the angle between the superior suture material and the bone as tensile loads increase. The suture material then hooks the tendon more firmly to the bone, increasing footprint compression. This is called the wedge effect (►**Fig. 3**).[35]

A similar mechanism may exist in SR repairs, in which the suture loop elongates under load. The upper limb creates a relative compression vector and a so-called focal loop wedge effect[48] (►**Fig. 4**).

Finally, a larger suture width can also increase self-reinforcement, since the wider diameter provides a larger surface area in contact with the tendon, increasing the other two mechanisms.[35]

Smith et al.[30] confirmed that self-reinforcement occurs in rotator cuff repairs using DR suture bridge with or without medial row knots; the performance load approached the final load at failure, and the rate of progression of footprint compression was higher for the knotless repair group. This provides biomechanical evidence that the self-reinforcing mechanism decreases by knotting the medial row, probably due to a tenodesis effect; therefore, a suture bridge repair without medial knots has the same biomechanical resistance but with improved pressure magnitude and distribution at the tendon-footprint interface; in addition, there is less tendon folding and, theoretically, better tendon irrigation, potentially favoring healing of the rotator cuff in all aspects.

Considering the studies analyzed, the use of a TOE configuration with tape and no medial row knots probably results in the best biomechanical conditions of contact area and pressure at the tendon-footprint interface. In addition, knot slippage and overstressing in arthroscopic repairs can cause small soft-tissue tears and generate a high concentration of stress. Additionally, braided sutures have been reported to have higher abrasive properties throughout rotator cuff tissue compared to monofilament sutures.[22] Tape has a higher mean load at failure and a greater contact area at the suture-tendon interface, facilitating the even distribution of pressure.[22] Mook et al.[49] presented in detail this surgical technique with a self-reinforcing concept, with excellent outcomes. However, it is important to consider tendon irrigation and how it may be compromised by increased compression at the tendon-footprint interface. Kim et al.[50] analyzed the biomechanical strength and histological results in a rabbit model, showing that medial row failure (intrasubstance tear) was more frequent in a suture bridge construct with knots; this was attributable to a microvascular compromise (lower number of vessels on histology). Unfortunately, there are no papers comparing the effect on irrigation of a medial row knotless configuration, and the benefits are only theoretical.

An interesting point to consider is the delamination of the rotator cuff. It is described as a horizontal tear between the layers of the rotator cuff,[43] and its prevalence ranges from 38% to 88%.[44] Pauzenberger et al.[27] demonstrated that a specific knotless, double-layer repair could anatomically restore the static restraint provided by the superior joint capsule and the dynamic appearance of the rotator cuff facilitated by the bursal side tendon layer, while combining the benefits of repair configurations without knots with the fixation force of a medially-knotted TOE repair. Therefore, a TOE repair alone is probably not enough to optimize outcomes, and an articular plate intervention must be added for technical improvement.

Lastly, the effect of abduction on the different types of constructs must be considered. The studies herein analyzed often showed that abduction did not affect self-reinforcement in knotted medial rows, in accordance with the idea that they can cause repair tenodesis, inhibiting the self-reinforcement mechanism. Abduction significantly decreases self-reinforcement in knotless repairs; this should be considered when indicating passive mobility and immobilization during the first postoperative weeks.

Conclusion

Contact area and pressure at the tendon-footprint interface is contingent to the surgical technique and its execution by the surgeon. Based on the biomechanical studies herein reviewed, we conclude that constructs that improve these aspects are those including a DR, TOE repair with no medial row knots and favoring tapes, specific repair concepts for delaminated tears, and abduction limitation during the immediate postoperative period.

Conflict of Interests

The authors have no conflict of interests to declare.

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