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Original Article

Biomechanical evaluation of surgical techniques for Achilles tendon repair: a laboratory study in bovine tendons

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Abstract

Objective: To compare the biomechanical performance of three tendon suture techniques in bovine specimens. The parameters used were elongation after loading, the stiffness of the construct, the maximum force, and the type of suture failure.

Method: A complete transection distant 5 cm from the distal bone insertion was made in thirty-six bovine Achilles tendons which were subsequently repaired using Vicryl®#2 sutures in three different ways: Group 1, simple shoelace suture (SS); group 2, triple shoelace suture (TP) and group 3, Carmont & Mafulli suture (CM). All the tendons were submitted to the same biomechanical tests.

Results: The tendon elongation was 5.9 mm in group 1 (SS), 3.0 mm in group 2 (TS), and 3.8 mm in group 3 (CM), with statistical significancy between group 2 and groups 1 ($p = 0.0037$) and 3 ($p = 0.0005$). Regarding the system stiffness, group 1 presented 23.2 N/mm, group 2, 30.3 N/mm, and group 3, 28.6 N/mm, with statistical significancy of groups 2 ($p < 0.0001$) and 3 ($p = 0.0075$) in relation to group 1. The maximum strength results were 158.2 N in group 1, 346.5 N in group 2, and 146.1 N in group 3, with statistical significancy between group 2 and groups 1 ($p < 0.0001$) and 3 ($p < 0.0001$). The type of rupture failure was statistically significant among all studied groups.

Conclusion: The increased number of sutures decreased the elongation and increased the construct stiffness, com statistical significancy of groups 2 and 3 over group 1. The higher resistance to failure in group 2 (346.5 N) was due to its symmetry and the higher number of sutures passed through both tendon stumps. The TS suture technique showed the lower elongation index (3.0 mm), the greater system stiffness (30.3 N/mm), the maximum force (356.6 N), and proportionality between the types of system failures (suture failure or tendon pullout).

Level of Evidence V; **Therapeutic Studies; Expert Opinion.**

Keywords: Achilles tendon; Biomechanics; Rupture, Tendon suture

Introduction

The frequency of Achilles tendon rupture has raised in the last decades due to the increase in physical activity and encouragement to practice sports in all ages and all around the world. Surgical treatment has become the preferred option for active patients[1] looking to regain their pre-injury activity level faster[2] and percutaneous surgical techniques have gained more popularity, due to the lower complication rates[3,4].

Percutaneous sutures with nonabsorbable threads for Achilles tendon repair present greater resistance to failure[5], but sural nerve entrapement can occur, representing a complication that often requires an extra surgical procedure to decompress the nerve. To reduce this complication, absorbable threads are indicated[6,7] due to a 75% resorption rate around five weeks[8]. Absorbable threads exhibit reduced tensile strength and mechanical durability over a shorter timeframe[8]. The

Study performed at the Laboratório de Biomecânica da Universidade Federal, Florianopolis, SC, Brazil.

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literature on the subject suggests that by using a greater number of suture threads crossing the tendon rupture site (6 to 8 threads) one can achieve greater resistance to failure at levels higher than the tensions necessary for normal walking with the knee completely extended[9-11].

Biomechanical studies are relevant to determine the suture resistance in the Achilles tendon and, consequently, the possible tensile load on the repair site, but generally, these tests are in the bovine tendon[10-13], they are usually healthy, promoting greater stiffness in the suture system and lower tendon pullout rate, contrasting with greater disorganization of tendon fibers in Achilles tendon ruptures in humans[14,16].

Percutaneous techniques with absorbable sutures are described in different contexts[6,7,11-13,17]. Intratendinous sutures are noted for their minimal disruption to peritendinous circulation and ability to establish a larger contact surface between the tendon and the suture used for repairing the rupture. This approach diminishes the risk of tendon pullout and elongation, thereby preserving the tensile strength post-tendon repair[18,19]. According to the literature, the increased number of threads and knots in the suture enhances the overall strength of the construct and the anchoring system, thereby reducing the risk of failure. This improvement is attributed to the increased suture stability within the tendon stumps and the more efficient distribution of tension absorption across the entire construct, including the anchorage points between the proximal and distal threads of the system[9,20].

The objective of this study was to compare the biomechanical performance of three different tendon suture techniques on bovine Achilles tendons, using data relative to the tendon elongation after loading, the stiffness of the whole system, the maximum force, and types of system failures.

Methods

Preparation of the samples

Thirty-six pieces of bovine Achilles tendons were included, aged between 14 and 20 months, submitted to a cooling period of 24 hours at a temperature of -5 degrees[14,18]. The pieces were prepared promptly to maintain the viscoelastic characteristics of the tendons[14,18,21].

The bovine Achilles tendon was measured with a digital caliper (accuracy of 0.01 cm). The length, width, and thickness of the tendons 5 cm proximal from their insertion were measured. A model of the Achilles tendon rupture was created, performing a transverse cut at this point. After, all pieces were prepared to receive the types of sutures and start the biomechanical test[22,23].

The samples were randomly divided into three groups: group 1 in which a simple shoelace suture (Bunnell) was done (SS)[7], group 2 in which a triple shoelace was used (TP), and group 3, in which a Carmontt and Mafulli (CM) tendon suture was performed[24].

Surgical techniques

The SS Bunnell's technique[7] is a modification of the Ma & Griffith's technique[6,7] (group 1), consisting of suturing with a Vicryl® #2 thread with multiple sutures in crisscross shape. The technique starts with a curved needle, intramural entry, and ipsilateral exit, followed by a straight needle and proximal oblique crisscrosses sutures on three levels. A transverse incision is performed at this moment, and oblique crisscross sutures are performed distal equally to the proximal sutures. Again, with a curved needle, a suture is made from the contralateral side to the intramural face of the rupture. The procedure is repeated in the distal stump, imitating a lace image in each tendon stump (Bunnel type) and finally tying the suture on both sides (Figure 1A).

The TS technique (group 2) consisted of suturing with two pairs of three Vicryl®#2 threads, marked as smooth, with one and two knots at both ends of the threads. The technique follows the SS passes, starting with the three threads passing the first and second sutures; at this point, the threads (two knots) are released. In the next suture, we leave the thread (a knot) on the ipsilateral side. Next, one more suture is performed with a smooth thread facing the distal equal to the SS. At this moment, the thread (one knot) is passed transversely and relocated in the needle and passed to distal with two threads and repeated with the thread (two knots), and again having three threads in the needle, following the SS technique, finishing three levels of suture and with six ends of intramural thread from the tendon rupture. We repeat the procedure with the same thread configurations and passes in the distal stump, performing a suture of a similar configuration in both stumps. The threads are identified at this moment, and suturing is performed in pairs according to the number of knots. The suture of the thread pairs proceeded from the most distal to the proximal to the site of the tendon rupture (Figure 1B).

In group 3, suturing was performed according to the Carmont & Mafulli's technique[24] using two pairs of four Vicryl®#22 threads for suturing the tendon, starting with

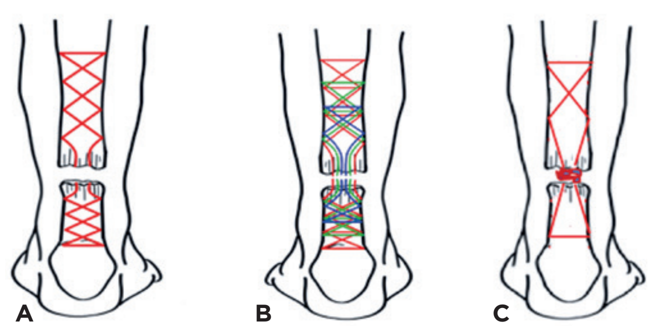

Figure 1. (A) Bunnell's suture technique (SS) (Edward T Mah), (B) triple shoelace technique (TS), (C) Carmont & Mafulli's technique (CM).

sutures in the proximal stump with threads transverse proximally to the rupture site and both ends of the suture threads are crossed in the distal direction, and a new suture is made diagonally in the direction of the rupture site distally (Bunnell suture type). In the distal stump, threads are passed in the transverse direction closest to the tendon insertion and followed by a diagonal suture in a proximal direction to the rupture site (Kessler's suture type) and sutured in two knots sets of the eight suture threads (Figure 1C).

Biomechanical testing

The tendons were fixed in a universal testing machine, Shimadzu AGS-X® 100kN (Shimadzu Corporation, São Paulo, Brazil), using Trapeziumx® software with a maximum load cell capacity of 1 kN. The tendons were subjected to axial force, initially at a constant load of 50 N for 300s (elongation measured). Afterward, the traction test was performed in displacement control, with a constant speed of 500 mm/min and passive force monitoring. The test is finalized after construct failure. With the data obtained, the Force Courve (force (N) vs. displacement in millimeters) were obtained to calculate the system stiffness parameters and maximum force supported by the construct. After the biomechanical tests, all pieces were evaluated for the type of system failure: (1) suture failure or (2) tendon pullout(12,18,26).

Statistical analysis

For statistical analysis**,** Microsoft Excel® (Microsoft Corporation, Redmond, Washington, USA) software was used. The Shapiro-Wilk normality test was used as a reference. We examined the distribution of data related to the thickness, width, and length of the tested Achilles tendons, considering various anatomical patterns as potential sources of bias. The f-test was used to hypothesize equality between the means of the measured parameters. The t-test was used to compare biomechanical variables among groups. Fisher's exact test was used to evaluate the failures observed after the rupture of the specimens. For all statistical tests, $p < 0.05$ was considered statistically significant.

Results

The anatomical characteristics of the tendons showed similarities in length, thickness, and width, as shown in Table 1.

The results of the tendon elongation at initial load had a mean of 5.9 mm in group 1, 3.0 mm in group 2, and 3.8 mm in group 3 (CM), the system stiffness had a mean of 23.2 N/mm in group 1, -30.3 N/mm in group 2, and -28.6 N/mm in group 3. The mean results of the maximum load force were 158.2 N in group 1, 346.5N in group 2, and 146.1N in group 3 (Figure 2A-C and Table 2).

The type of system failure was evaluated for suture rupture, with 11 in group 1 and seven in group 2. The tendon pullout was presented in one construct in group 1, five in group 2, and all constructs in group 3 (Table 3).

The statistical analysis focuses on the results categorized by data group, including tendon elongation, system stiffness, maximum load force (Table 4), and the type of system failure (Table 5).

Discussion

The type of suture in Achilles tendon repair is still widely discussed, and percutaneous techniques are increasingly adopted(4-7,13,24). The resistance of sutures in percutaneous techniques has always been questioned regarding the reliability of the construct. Using sutures with non-absorbable thread, such as the Achillon or PARS techniques(14,17), shows increased resistance in the sutures, making them more reliable. However, they may have a longer reaction period and higher complication rates. Carmont et al.(6,24) suggested using absorbable suture thread to reduce complications and increase the number of threads to a better suture resistance(4,9,25,26).

The standard use of absorbable sutures (Vicryl®#2) in our study was due to its presentation of resorption of 75% in five weeks and its entirety in approximately 90 days (8). This resorption process leads us to believe in lower complication rates, such as neurological injury and shorter periods of the local reaction process. Consequently, it presents lower suture resistance(15,18) compared to non-absorbable sutures(6,10,14). The tendons tested in group 2 showed a high resistance index (346.5N), a value above that described by biomechanical studies (range 228.60 N–245 N(10-13.23,25,26) and clinical studies(11.27) considering the knee in extension and the ankle at 0 degrees with a value of 70.6 N and at 10 degrees of dorsiflexion of 183.2 N. Groups 1 (158.2 N) and 3 (146.1 N) were shown to be close to those described by Oroshimo et al.(11). The results lead us to interpret that the three techniques are applicable in Achilles tendon repair. However, only the result found in group 2 allows us to consider that the resistance obtained in this suture allows us to use early loading on the repaired tendon.

Table 1. Anatomical values of tendons by group, where T is the thickness, W is the width, and L is the length. All measurements are in millimeters.

	Group 1			Group 2			Group 3		
	T*	W*	L*	T*	W*	L*	T*	W*	L*
Mean [mm]	9.90	13.01	137.85	9.89	14.23	129.93	7.25	11.86	117.63
Standard deviation [mm]	3.09	3.60	10.02	1.15	1.67	10.10	1.43	1.95	14.06

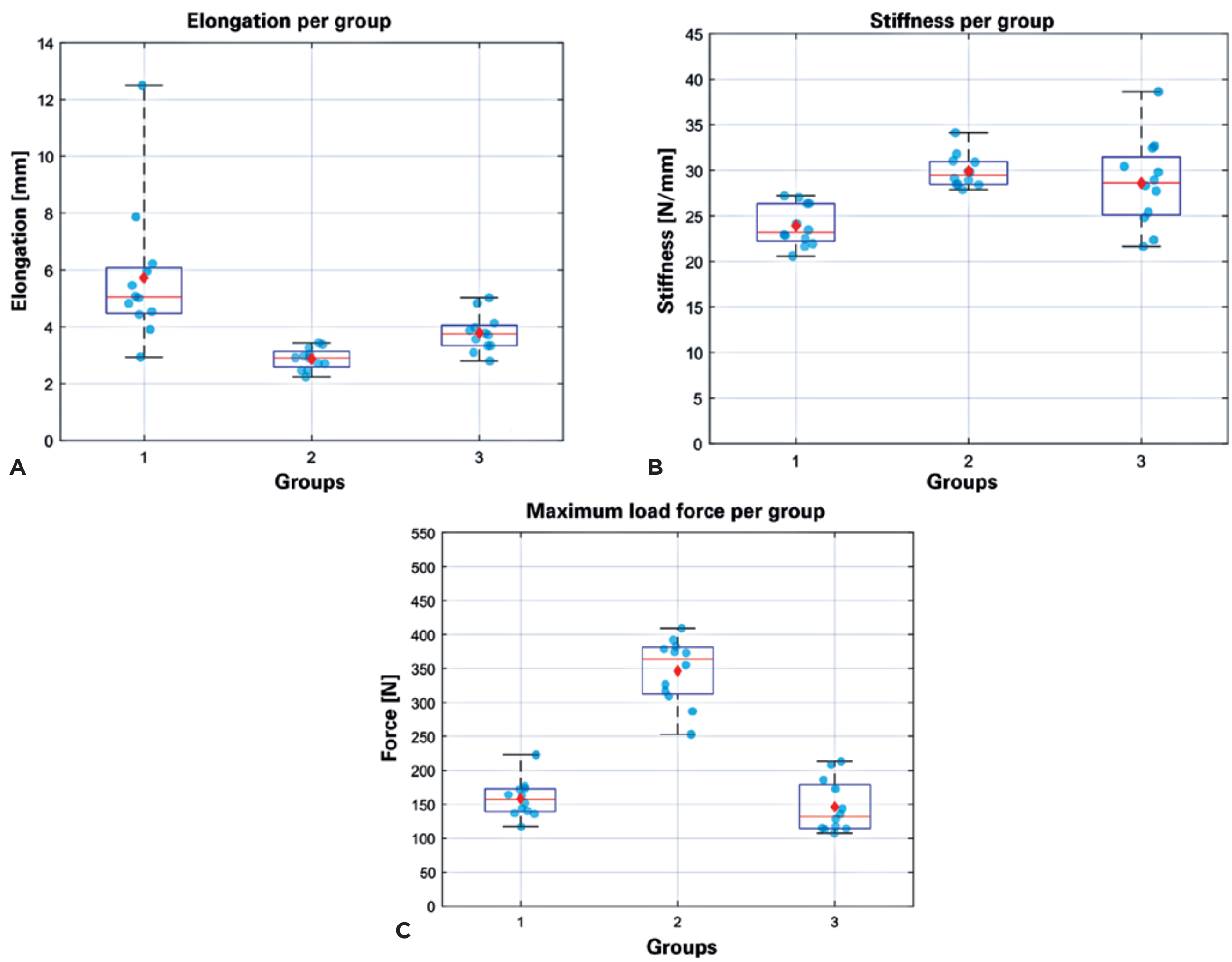

Figure 2. (A) Boxplot displaying the elongation between the tendon stumps during the constant load phase of 50 N for 300s. (B) Stiffness of the sutured tendons among the groups recorded in Nmm. (C) Maximum load force required for system failure. The red center horizontal line indicates the median and the box's lower and upper blue edges indicate 25% and 75%, respectively. The lines extend to the most extreme data points. The diamond-shaped point represents the mean value, and the spherical points represent each data point.

Table 2. Mean values and standard deviation (SD) of the biomechanical data for the Elongation, system stiffness, and maximum force of the test samples

Group (n = 12)	Elongation		Stiffness		Full Strength	
	Mean [mm]	SD [mm]	Mean [N/mm]	SD [N/mm]	Mean [N]	SD [N]
1	5.9	2.5	23,2	2.8	158.2	27.5
2	3.0	0.4	30.3	1.1	346.5	47.6
3	3.8	0.7	28.6	4.8	146.1	38.8

SD: Standard deviation.

Table 3. Type of failure in all groups

Failure mode	Group 1 (SS)	Group 2 (TS)	Group 3 (CM)
Suture rupture	11	7	0
Tendon pullout	1	5	12

Clinically, tendon elongating greater than 5 mm may decrease the performance of the technique, as described by Kangas et al. (19). Therefore, we consider elongation ≥ 5 mm as a system failure in our series. In our study, groups 2 and 3 showed elongations less than 5 mm (means of 3.0 mm and 3.8 mm, respectively). According to published studies [(6,9,12,23)], rising threads in the sutures increase the strength under low cyclic stresses. This fact corroborated with the result of the mean elongation of 5.9 mm in group 1, which can be considered

Table 4. The p-value in the statistical tests among the groups regarding the means for elongation, system stiffness, and maximum force load

Groups	Elongation		Stiffness		Maximum load	
	f-test	t-test	f-test	t-test	f-test	t-test
1-2	< 0.0050	0.0037	0.48	= 0	1494	= 0
1-3	0.0001	0.0210	0.0213	0.0075	0.2638	0.3915
2-3	0.0795	0.0005	0.0032	0.3849	0.5077	= 0

Table 5. The p-values in the statistical tests among the groups (Fischer's exact test)

Groups	Fisher's exact test
1-2	0.0730
1-3	= 0
2-3	0.0046

a system failure. Our study was statistically significant when comparing groups 1 vs. 2 ($p = 0.0038$) and 1 vs. 3 ($p = 0.0210$). Therefore, as described in the literature[9], using four and six sutures resulted in lower elongation of the repaired tendons. When we evaluated the results between groups 2 vs. 3 ($p < 0.001$), which also was statistically significant, we can consider that the increased number of threads in the suture is not the only factor determining the final elongation in the sutured tendon.

The mean system stiffness in our study was different among the groups: group 1 (23.2 N/mm), group 2 (30.3 N/mm), and group 3 (28.6 N/mm). Groups 2 and 3 presented greater rigidity with a relevant difference to group 1, statistically significant between groups 1 and 2 ($p < 0.0005$) and 1 vs. 3 ($p = 0.0075$). The result demonstrated that the number of sutures is directly related to the system's rigidity. The comparison of the system stiffness of groups 2-3 ($p = 0.3845$) showed no statistical difference. However, using three threads (group 2) showed a higher construct stiffness value than four threads (group 3). This leads us to believe that the symmetrical suture in both stumps promoted greater rigidity due to the similarity in the passes of the intratendinous suture and with greater suture attachment points within the stumps, promoting greater stability to the tendon and, consequently, the better distribution of system forces. Our results align with biomechanical studies demonstrating that systems with suture symmetry in both stumps behave more stably and with lower displacement[14,20,26]. Our results suggest that the TS technique (group 2) promotes a more stable construct, allowing early mobilization and loading[2].

In our study, the use of threads was standardized (Vicryl®#2) for all groups, and our objective was to compare the final mechanical strength performed in each construct[9,12,23]. The comparative analysis between the final resistance of group 1 (158.2 N) and group 2 (346.5 N) showed a statistically significant difference ($p < 0.0050$), confirming that the increased number of threads in the same type of suture system increases the resistance of the construct performed. When the results between group 1 (158.2 N) and group 3 (146.9 N) were compared, no statistically significant difference ($p = 0.3915$) was observed between the two groups, indicating that the number of threads was not the primary factor, evidenced by the type of suture used in group 1, where it presented the same resistance to the use of four threads in group 3. Therefore, the greater number of sutures in the tendon probably determined greater stability of the suture-tendon set, promoting increased resistance to the construct. The importance of the type of suture used in improving the resistance is evident when comparing the results between groups 2 (346.5 N) and 3 (146.1 N), which showed a statistically significant difference ($p < 0.0050$), demonstrating that the increase in the number of sutures in the tendon and in a symmetrical way of the construct in both stumps promotes greater stability of the threads-tendon construct, showing to be a more important factor than the number of threads used to increase the resistance of tendon repair, demonstrated by the use of a smaller number of threads in the TS technique than in Group 3.

The distribution of system failures, as outlined in the literature, exhibited varying frequencies within the groups. These frequencies were attributed to either suture rupture or tendon pullout, and they were influenced by factors such as the extent of elongation and system stiffness. In group 1, most cases (11 out of 12) were associated with suture rupture, likely due to the high elongation and low system stiffness. However, this difference was not statistically significant compared to group 2 ($p = 0.0730$). This observation is likely attributable to the relatively low final resistance of the system. In group 3, all tests (12 pieces) showed tendon pullout in the distal stump. Consequently, we infer that the low elongation in this group, resulting from increased stiffness at the tying point of the four grouped threads and the mean stiffness within the construct, is indicative of the elongation being primarily caused by the single-pass suture in the distal stump, leading to system failure due to its lower stiffness. This result is statistically significant compared to group 1 ($p < 0.0050$), despite increased threads and similar final resistance between groups 1 and 3. The pieces studied within group 2 showed a slight predominance of suture rupture (7 pieces) over tendon pullout (5 pieces). These cases demonstrated less elongation and greater rigidity within the system due to a better distribution of tension forces between the suture and the tendon, not statistically significant compared to group 1 ($p = 0.0730$) and statistically significant compared to group 3 ($p = 0.0046$). These results suggest that the simple suture method carries a higher risk of construct rupture, which, *in vivo*, could manifest as an increased likelihood of tendon re-rupture. In contrast, group 3 experienced progressive tendon pullout in the distal stump, causing elongation of the construct onto the tendon. This elongation appears to be directly proportional to the greater loss of muscle strength in the repaired tendon. The findings regarding system failure in group 2 highlight that multiple levels and passes of the suture more effectively distribute forces through the tendon, thus safeguarding the integrity of the Achilles tendon repair against elongation.

Surgical Achilles tendon repair aims to accelerate the reorganization of tendon fibers and the recovery of tendon tension. Biomechanical studies collaborate clinically by evaluating the repair systems: the greater load resistance, the lower traction forces failure, the potential of the system stiffness in preventing tendon elongation, and the consequent loss of muscle force transmission. The TS technique (Group 2) showed a 3.0 mm elongation, below the limit for suture failure described in the literature (5 mm). The system stiffness was 30.3 N/mm, demonstrating a good suture and with a mean of 345 N failure resistance, close to non-absorbable sutures[25] and above the values described in biomechanical studies[10,12,14,15,23] and clinical studies[9,11,27]. We believe these results demonstrate the applicability of this technique for Achilles tendon repair with safety and the ability to support loading and early mobilization. This is reflected in the type of system failure observed in this group, where system rupture was the most common, although it typically occurred at loads exceeding those encountered during daily activities. However, due to tendon pullout failures, it is crucial to exercise caution and protect dorsiflexion until the repaired tendon fully regains its continuity. The biomechanical results found in our study lead us to consider that the triple shoelace technique is reproducible *in vivo* and safely using a rehabilitation protocol with equine load, early mobilization, and dorsiflexion protection until strength gain of the gastrocnemius soleus complex.

Conclusion

Our study demonstrated that an increased number of sutures decreased tendon elongation under load and increased construct stiffness in groups 2 and 3. The higher resistance of the suture until the system failure presented in group 2 (346.5 N) is above the other groups and in the literature for absorbable threads. The triple shoelace technique with multiple anchorages and symmetrically intratendinous sutures demonstrated a lower elongation index (3.0 mm), greater system stiffness (30.3 N/mm), and proportionality in the type of system failures. The high resistance until the system failure (346.5 N) is due to the more uniform distribution of tension between the suture and the knots in a paired way. The triple shoelace technique requires clinical studies to prove reproducibility *in vivo*.

Authors' contributions: Each author contributed individually and significantly to the development of this article: MKA *(https://orcid.org/0000-0002-2555-9594), and APGS *(https://orcid.org/0000-0001-7122-1984) and MRD *(https://orcid.org/0009-0003-8185-7005) and CRMR *(https://orcid.org/0000-0002-9430-7059) Conceived and planned the activities that led to the study, wrote the article, participated in the review process, approved the final version; MGA *(https://orcid.org/0000-0001-5650-4564) Data collection, wrote the article, approved the final version. All authors read and approved the final manuscript.*ORCID (Open Researcher and Contributor iD).

References

1. Deng S, Sun Z, Zhang C, Chen G, Li J. Surgical treatment versus conservative management for acute Achilles tendon rupture: a systematic review and meta-analysis of randomized controlled trials. J Foot Ankle Surg. 2017;56(6):1236-43.
2. Kearney RS, Costa ML. Current concepts in the rehabilitation of an acute rupture of the tendo Achillis. J Bone Joint Surg Br. 2012;94(1):28-31.
3. Rozis M, Benetos IS, Karampinas P, Polyzois V, Vlamis J, Pneumaticos SG. Outcome of percutaneous fixation of acute Achilles tendon ruptures. Foot Ankle Int. 2018;39(6):689-93.
4. Haje DP, Haje, SA, Porto, AO, Silva CV. Percutaneous suture of Achilles tendon by modified Ma-Griffith technique: results' evaluation. Rev Bras Ortop 2005;40(4):162-74.
5. DeVries JG, Scharer BM, Summerhays BJ. Acute Achilles rupture percutaneous repair: approach, materials, techniques. Clin Podiatr Med Surg. 2017 Apr;34(2):251-62.
6. Carmont MR, Rossi R, Scheffler S, Mei-Dan O, Beaufils P. Percutaneous & mini invasive Achilles tendon repair. Sports Med Arthrosc Rehabil Ther Technol. 2011;3:28.
7. Ng ES, Ng YO, Gupta R, Lim F, Mah E. Repair of acute Achilles tendon rupture using a double-ended needle. J Orthop Surg (Hong Kong). 2006 Aug;14(2):142-6.
8. Barros M, Gorgal R, Machado AP, Correia A, Montenegro N. Surgical basic skills: surgical sutures. Acta Med Port. 2011;24 Suppl 4:1051-6.
9. Carmont MR, Zellers JA, Brorsson A, Olsson N, Nilsson-Helander K, Karlsson J, et al. Functional outcomes of achilles tendon minimally invasive repair using 4- and 6-strand nonabsorbable suture: a cohort comparison study. Orthop J Sports Med. 2017;5(8):2325967117723347.
10. Guzzini M, Lanzetti RM, Proietti L, Mazza D, Fabbri M, Monaco E, et al. Interlocking horizontal mattress suture versus Kakiuchi technique in repair of Achilles tendon rupture: a biomechanical study. J Orthop Traumatol. 2017;18(3):251-257.
11. Orishimo KF, Burstein G, Mullaney MJ, Kremenic IJ, Nesse M, McHugh MP, et al. Effect of knee flexion angle on Achilles tendon force and ankle joint plantarflexion moment during passive dorsiflexion. J Foot Ankle Surg. 2008;47(1):34-9.

12. Ortiz C, Wagner E, Mocoçain P, Labarca G, Keller A, Del Buono A, et al. Biomechanical comparison of four methods of repair of the Achilles tendon: a laboratory study with bovine tendons. J Bone Joint Surg Br. 2012;94(5):663-7.
13. Wang T, Mu Y, Diao Y, Liu W, Wu Y, Wang Z, et al. Biomechanical comparison of panda rope bridge technique and other minimally invasive Achilles tendon repair techniques in vitro. Orthop J Sports Med. 2021;9(6):23259671211008436.
14. Heitman DE, Ng K, Crivello KM, Gallina J. Biomechanical comparison of the Achillon tendon repair system and the Krackow locking loop technique. Foot Ankle Int. 2011;32(9):879-87.
15. Yang CC, Yu X, Guo ZH, Fu YW. The biomechanical study of rupture of Achilles tendon and repair by different suture techniques. Pak J Med Sci. 2018;34(3):638-642.
16. Zhang J, Xie B, Xi Z, Zhao L, Cen L, Yang Y. A comparable study of polyglycolic acid's degradation on macrophages' activation. Mater Sci Eng C Mater Biol Appl. 2020;109:110574.
17. Clanton TO, Haytmanek CT, Williams BT, Civitarese DM, Turnbull TL, Massey MB, et al. A biomechanical comparison of an open repair and 3 minimally invasive percutaneous Achilles tendon repair techniques during a simulated, progressive rehabilitation protocol. Am J Sports Med. 2015;43(8):1957-64.
18. Nyström B, Holmlund D. Separation of tendon ends after suture of Achilles tendon. Acta Orthop Scand. 1983;54(4):620-1.
19. Kangas J, Pajala A, Ohtonen P, Leppilahti J. Achilles tendon elongation after rupture repair: a randomized comparison of 2 postoperative regimens. Am J Sports Med. 2007;35(1):59-64.
20. Wagner P, Wagner E, López M, Etchevers G, Valencia O, Guzmán-Venegas R. Proximal and distal failure site analysis in percutaneous Achilles tendon rupture repair. Foot Ankle Int. 2019;40(12): 1424-1429.
21. Matthews LS, Ellis D. Viscoelastic properties of cat tendon: effects of time after death and preservation by freezing. J Biomech. 1968;1(2):65-71.
22. O'Brien M. The anatomy of the Achilles tendon. Foot Ankle Clin. 2005;10(2):225-38.
23. Lee SJ, Goldsmith S, Nicholas SJ, McHugh M, Kremenic I, Ben-Avi S. Optimizing Achilles tendon repair: effect of epitendinous suture augmentation on the strength of Achilles tendon repairs. Foot Ankle Int. 2008;29(4):427-32.
24. Carmont MR, Maffulli N. Modified percutaneous repair of ruptured Achilles tendon. Knee Surg Sports Traumatol Arthrosc. 2008;16(2):199-203.
25. Van Dyke RO, Chaudhary SA, Gould G, Trimba R, Laughlin RT. Biomechanical head-to-head comparison of 2 sutures and the Giftbox versus Bunnell techniques for midsubstance Achilles Tendon ruptures. Orthop J Sports Med. 2017;5(5):2325967117707477.
26. Tian J, Rui R, Xu Y, Yang W, Chen X, Zhang X, et al. Achilles tendon rupture repair: Biomechanical comparison of the locking block modified Krackow technique and the Giftbox technique. Injury. 2020;51(2):559-64.
27. Bäcker HC, Yenchak AJ, Trofa DP, Vosseller JT. Strength measurement after Achilles tendon repair. Foot Ankle Spec. 2019;12(5):471-9.