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Review

Biomechanical comparison of shoelace suture technique for repairing calcaneal tendon

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ABSTRACT

Background: The biomechanical assessment of tendon repair is essential for the evaluation of different tendon suturing techniques. The shoelace suture technique with absorbable Vicryl® is a modified technique of Achilles tendon repair that may have biomechanical advantages depending on the number of threads used and the direction of the suture.
Purpose: To evaluate the creep under constant pre-load, the stiffness, the maximum strength, and the failure mode for three different configurations of the shoelace suture in a bovine tendon biomechanical model.
Study design: Controlled Laboratory Study.
Methods: 36 bovine Achilles tendon specimens were acquired and divided into three test groups of 12 Achilles tendons each. A model of the calcaneal tendon rupture was created through a transverse cut with a scalpel, performed 5 centimeters proximal to the calcaneal bone insertion. Group 1 was repaired using the simple shoelace technique with just one suture. Group 2 was repaired using the shoelace technique with three sutures individually sutured from distal to proximal at the site of rupture. Group 3 was repaired using the shoelace technique with three sutures individually sutured from proximal to distal at the site of rupture.
Results: System creep after constant pre-load was 5.9 ± 2.5 mm, 3.0 ± 0.4 mm and 2.9 ± 0.4 mm for groups 1, 2 and 3, respectively. The system's stiffness was 23.2 ± 2.8 N/mm, 30.3 ± 1.1 N/mm and 29.8 ± 2.3 N/mm for groups 1, 2 and 3, respectively. In the final load-to-failure test, the ultimate load force (ULF) was 158.2 ± 27.5 N, 346.5 ± 47.6 N and 358.1 ± 41.6 N for groups 1, 2 and 3, respectively. There was statistical significance in the comparative tests between groups 1-2 and 1-3 in terms of means of creep, system stiffness and maximum system strength. No statistically significant difference was found between groups 2 and 3 when analyzing creep, system stiffness and ULF. Suture breakage was the prevalent mode of failure for all tested groups.
Conclusion: The shoelace with three sutures significantly reduced creep in the preloading phase and increased the stiffness and ultimate load force. The biomechanical results demonstrate better overall mechanical performance of the technique than the simple shoelace technique. The better mechanical performance indicates that the shoelace with three sutures could result in early postoperative rehabilitation.
Clinical relevance: This study indicates that the shoelace suture technique with three sutures is biomechanically strong and stiff, being a possible therapeutic option to be used.

Introduction

There is a wide range of surgical treatments for Achilles tendon rupture from conservative to open or percutaneous surgical techniques [1]. The aim is to repair the integrity of the tendon through sutures, seeking to restore its previous length and biomechanical properties as close as possible to that of a healthy tendon [2]. Sutures with good tensile strength are desirable since they allow early force loading on the tendon, thereby minimizing the recovery period and complications, allowing for early force loading on the tendon, thereby minimizing the recovery period and complications [3].

The vascularization of the Achilles tendon is primarily peritendinous

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on its anterior surface [4] and extensive dissection and suture on the volar surface may decrease vascularization during Achilles tendon repair [5]. Due to this factor, intratendinous sutures result in less damage to the vascularization of the Achilles tendon [6].

The type of suture material used should consider the local inflammatory reaction process, which may vary in intensity depending on the properties of the suture material [7]. Key points for a satisfactory repair relies on the strength of the suture and the transmission mode of tensile forces to the injured body of the tendon after its repair [8].

Non-absorbable sutures (such as FiberWire®) have greater mechanical strength but lose a considerable amount of this strength after a knotting [9]. On the other hand, absorbable sutures lose part of its strength as the tendon undergo repair due to reabsorption. This process lowers the stress concentration caused by the suture further contributing to a briefer inflammatory period.

Vycril® show a total degradation period between 75 to 90 days, and when Maxon® is used, between 90 to 120 days, promoting a shorter inflammatory period for the suture material [7]. Vycril® exhibits a 75 % decrease in tension in five weeks, minimizing ischemic complications [10,11] and possible compression of the sural nerve [12].

Several studies have biomechanically evaluated the different types of calcaneal tendon sutures in animal models [13,14]. These studies assessed which configuration and surgical technique have a lower chance of failure when the tendon is subjected to load. However, biomechanical evaluations comparing different configurations of the shoelace suturing technique have not been performed. These evaluations are necessary to compare the biomechanical performance of these three surgical approaches, thus allowing the comparison of the similarity or superiority of one configuration to the other.

The purpose of this study was to biomechanically assess the system creep under constant pre-load, the system stiffness, resistance to failure and failure modes between the three distinct configurations of the shoelace Achilles suture technique with absorbable Vicryl® suture material.

Materials and methods

Biomechanical testing and statistical analyses were performed at the Biomechanical Engineering Laboratory of Federal University of Santa Catarina - Brazil. The animal ethics committee did not require authorization because this study evaluated bovine tendons acquired from commercial food establishments.

A total of 36 bovine Achilles tendon specimens, from animals aged between 14 and 20 months, were collected from a nearby abattoir for human consumption. After a cooling period of 24 hours at a temperature of -5°C, the anatomical specimens were dissected and wrapped in 0.9 % saline solution. The tendons were then randomly divided into 3 experimental groups with 12 specimens in each group. A model of rupture of the calcaneal tendon was created through a transverse cut with a scalpel performed 5 centimeters from its bone insertion [13]. A digital caliper with an accuracy of 0.01 mm was used to measure the length, width, and thickness of the tendons at the 5 cm portion from their insertion. The specimen preparation period was performed in a timely manner to maintain the viscoelastic characteristics of the tendons [15]. Time between end of preparation and biomechanical testing of the specimens was 20 ± 10 minutes. Three experienced orthopedic surgeons prepared the specimens for testing.

For Group 1 a simple shoelace technique with one suture was done. For group 2 a shoelace technique with three sutures were individually sutured from distal to proximal to the site of rupture. And finally, for group 3, similarly to group 2, a shoelace technique with three sutures going from proximal to distal.

The simple shoelace technique utilized in group 1 is a modification of Ma & Griffiths technique that involved suturing with a Vicryl® number 2 suture in a similar fashion at both the proximal and distal ends of the Achilles tendon rupture (Fig 1). The technique involves multiple passes of sutures, with the first step being the suture of the proximal end with a curved needle entering the intramural part of the rupture and exiting proximally on the outer surface of the same side as the entry (considered the ipsilateral side). The next step involves a straight needle "thread passer" passing the suture in a diagonal manner across the proximal end to exit on the contralateral surface. The third pass is again diagonal towards the proximal side to the ipsilateral surface, followed by the fourth pass diagonally towards the contralateral side. The fifth pass involves the suture crossing straight across the ipsilateral surface. At this point, the process is repeated in the distal end, creating the appearance of a shoelace at both ends of the rupture. Finally, both ends of the shoelace are sutured together.

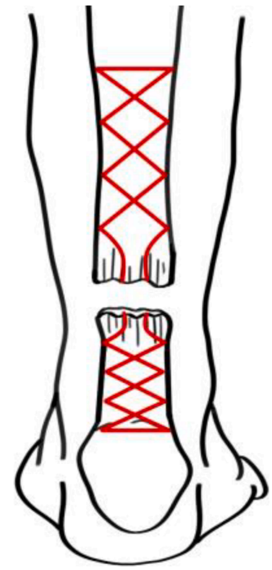

Fig. 1. Simple shoelace technique.

The "Triple Shoelace" technique (groups 2 and 3) involves using 6 vicryl® number 2 sutures (Fig. 2). Initially, two sets of three sutures are formed, which are marked at both ends of the suture as smooth, with one knot, and with two knots. The markings serve to facilitate identification of the sutures during the technique. The technique follows the same

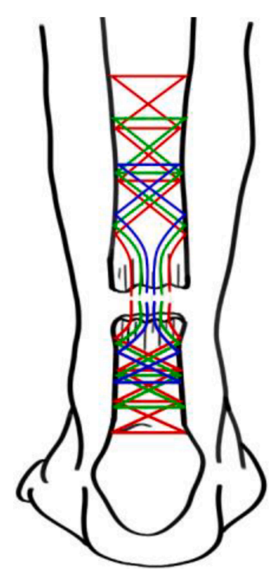

Fig. 2. Schematic drawing of the triple Shoelace suture. The Knot 2 sequence of suture thread Group 2 red, green and blue, Group 3 blue, green and red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

suturing pattern as the simple shoelace, with 3 sutures passed through the first and second passes, at which point the surgeon leaves the suture marked with two knots. Then, the third pass is made, leaving the suture marked with one knot on the ipsilateral side. The fourth, fifth, and sixth passes are the same as in the simple shoelace technique. At this point, after the sixth pass, the suture is transversely crossed with a knot and the needle is repositioned (6th pass), followed by the seventh pass in which two sutures are crossed and the suture with two knots is passed transversely. The technique then continues with the eighth and ninth passes, resulting in six suture ends on the inner surface of the tendon rupture. The procedure is repeated with the same suture configurations and passes on both ends of the rupture. At this point, the sutures are identified and paired according to the knot markings. In group 2, the pairs of sutures were then sutured from distal to proximal to the site of the tendon rupture (forming pairs of sutures in the sequence of no knot, one knot, and two knots). In group 3, the pairs of sutures were sutured from proximal to distal to the site of the tendon rupture (forming pairs of sutures in the sequence of two knots, one knot, and no knot).

The biomechanical test was performed on a Shimadzu AGS-X® 100kN universal testing machine, using Trapeziumx® software with a maximum load cell capacity of 1 kN, this force transducer has an accuracy of ± 0.5 % ranging from 20 N up to 1 kN. Prior to the test itself, a preload of 5 N was applied then followed by the preconditioning phase, during this phase, the specimens were subjected to a constant load of 50 ± 1 N for 300 s, followed by an acute tensile loading with a constant speed of the machine crosshead of 500 mm/min [12], with the passive monitoring of the force being recorded until total system failure. We considered the maximum force achieved, or the ultimate load force (ULF), as the maximum system strength. During the pre-conditioning phase the machine displacement was monitored, and the system creep measured. Calculation of system stiffness was done at the beginning of the ultimate loading leading to failure, between 50 N and 60 N. After the biomechanical tests, failure analysis was performed by assessing the repaired site, separating into two subgroups: Suture breakage and Suture pullout [13].

Shapiro-Wilk normality test was performed to observe a normal distribution of the thickness, width, and length data of the tested Achilles tendons, while mitigating different anatomical patterns as biases. The normality of the data distribution for the biomechanical characteristics of each group was also assessed using the Shapiro–Wilk test. Group variance was analyzed using the F-test. Mean difference was compared using the Student’s t-test, assuming equal variance. Three comparisons were done, between group 1 and group 2, then between group 1 and group 3, and finally between groups 2 and 3. The statistical hypothesis for Student’s *t-test* for means are listed below. For comparison between groups 1 and 2:

$$\begin{cases} H0: \mu^1_{creep} = \mu^2_{creep} \\ H1: \mu^1_{creep} \neq \mu^2_{creep} \end{cases}$$

$$\begin{cases} H0: \mu^1_{stiffness} = \mu^2_{stiffness} \\ H1: \mu^1_{stiffness} \neq \mu^2_{stiffness} \end{cases}$$

$$\begin{cases} H0: \mu^1_{ULF} = \mu^2_{ULF} \\ H1: \mu^1_{ULF} \neq \mu^2_{ULF} \end{cases}$$

Where the null hypothesis (H0) establishes that the true difference in means for the biomechanical variables is equal to zero, and the alternative hypothesis (H1) is that there is a statistically significant difference in means, the same logic is valid for the other 2 comparisons. For comparison between groups 1 and 3:

$$\begin{cases} H0: \mu^1_{creep} = \mu^3_{creep} \\ H1: \mu^1_{creep} \neq \mu^3_{creep} \end{cases}$$

$$\begin{cases} H0: \mu^1_{stiffness} = \mu^3_{stiffness} \\ H1: \mu^1_{stiffness} \neq \mu^3_{stiffness} \end{cases}$$

$$\begin{cases} H0: \mu^1_{ULF} = \mu^3_{ULF} \\ H1: \mu^1_{ULF} \neq \mu^3_{ULF} \end{cases}$$

For comparison between groups 2 and 3:

$$\begin{cases} H0: \mu^2_{creep} = \mu^3_{creep} \\ H1: \mu^2_{creep} \neq \mu^3_{creep} \end{cases}$$

$$\begin{cases} H0: \mu^2_{stiffness} = \mu^3_{stiffness} \\ H1: \mu^2_{stiffness} \neq \mu^3_{stiffness} \end{cases}$$

$$\begin{cases} H0: \mu^2_{ULF} = \mu^3_{ULF} \\ H1: \mu^2_{ULF} \neq \mu^3_{ULF} \end{cases}$$

The Fisher exact test was used for count data related to the observed failures modes after the rupture of the test specimens, whether the failures were due to the breaking of the suture threads (thread failure) or the pullout of the sutures through the tendon (tendon failure). All tests were performed using statistical analysis software (RStudio, version 1.1.456). For all statistical tests, a p-value < 0.05 was considered statistically significant.

Results

The anatomical characteristics of the tendons are shown in Table 1.

The biomechanical results are shown in Fig. 3A–C and compiled in Table 2. Sequentially to the biomechanical testing with the specimens, we analyzed the type of failure resulting in the contingency table 3. Data resulting from the statistical analysis are compiled in table 4 and 5.

Discussion

Several studies have evaluated the biomechanical behavior of calcaneal surgical repair techniques. The literature presents values of 228.60 N for “interlocking horizontal mattress” in Guzzini et al [20] and regarding continuous and abrupt tensile strength. In our study, the mean result for ULF in group 1 (158.2 ± 27.5 N) was well below that described in the literature. Considering that the absorption time of polyglycolic acid suture is between 75 and 90 days [7], we theorized that simple suture is not a safe option for repairing Achilles tendon rupture. The use of triple shoelace in group 2 (346.5 ± 47.6 N) and group 3 (358.1 ± 41.6 N) showed a statistically significant increase in tensile strength when compared to the results in group 1, and without significance when comparing the results between groups 2 and 3. These values are in agreement with those described in the literature, as demonstrated by Ortiz et al [13] who compared four suture techniques in bovine Achilles tendons, resulting in significantly greater mechanical resistance for the Dresden technique with triple suture averaging around 246.1 N (205 N to 309 N) until system rupture.

In the present biomechanical study, the Vicryl® 2 suture thread was standardized and employed in the same form of a shoelace cross-stitch in all groups, allowing for uniformity of the suture construct, differing only in the number of threads used with one thread for group 1 and three threads varying the direction of the suture for groups 2 and 3 (Table 1). The evaluation of the creep during the pre-conditioning phase showed that the single suture (group 1) resulted in a larger displacement under

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

	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	8.91	14.66	130.13
SD [mm]	3.09	3.60	10.02	1.15	1.67	10.10	1.39	1.47	16.38

load with 5.9 ± 2.5 mm, a significant difference compared to the triple shoelace suture in group 2 (3.0 ± 0.4 mm) and group 3 (2.9 ± 0.4 mm). There was no significant difference when comparing groups 2 and 3 (Table 4). Just as a Gap between the stumps is observed before the complete rupture of the tendon [18], a Gap value greater than 5 mm is considered a suture failure [19]. System creep might be an indicative of a gap formation, thus, system creep smaller than 5 mm from the second and third groups reinforce the argument that the 3-thread technique preserves the functional unit of the tendon. Therefore, we can determine that the 3-thread suture presented greater resistance and better stability of the construct to the injured tendon, agreeing with the literature that describes six knots present greater resistance to continuous cyclic movement. Ortiz et al [13] also observed a smaller gap when the triple-thread Dresden technique was used compared to other techniques. Tian et al [17] also visualized that reinforcements with additional sutures increase the strength of tendon repair compared to other techniques. The direction of the multiple-thread suture (groups 2 and 3) did not show a significant statistical difference in creep, demonstrating that the number of threads employed and the cross-stitch suture increased the stability of the construct and presented less distraction between the suture and the tendon. The distribution of the force employed at the different levels of suture performed was also considered an important factor for the stability of the system.

The stiffness of the system between groups 1 (23.2 ± 2.8 N/mm), group 2 (30.3 ± 1.1 N/mm), and group 3 (29.8 ± 2.3 N/mm) also showed statistical differences when comparing results between group 1 and 2 and between groups 1 and 3, which confirms the number of sutures has a direct relationship with the stiffness of the system, as seen in the work of Tian et al [17], where analysis of sutures with reinforcement showed similar stiffness values. The use of 3 suture threads increased the resistance of the system, as demonstrated by the higher stiffness and maximum load that could be applied before the onset of gap opening between the tendon stumps, as described in the literature. The use of 3 suture threads increased the stiffness of the system, as demonstrated by the no significant difference between groups 2 and 3 (even though the threads in group 3 had stepped tensioning), allowing us to describe that our results agree with the literature, () that the use of three threads increases the initial resistance, and it was indifferent to the sequential direction of the suture threads. The higher resistance found in our study with the triple shoelace suture supports our recommendation to prescribe early mobilization assisted by low tension on the tendon without loss of the construct used.

Another important finding was the failure patterns: suture rupture and pull-out, with suture rupture being the most frequent. There was no statistical predominance of kind failure pattern in one group over another, as demonstrated by the Fischer exact test, with a p-value greater than 0.05, but we noted the lowest incidence of suture rupture in the group 2. In absolute numbers, all three groups showed mostly suture rupture in the specimens, corroborating with similar studies by Thomas et al [21] and Guzzini et al [20], both of which demonstrated that suture failure was the predominant failure mode in the tested specimens. From the difference in data distribution of groups 2 and 3 for the stiffness, we can hypothesize that the direction of suture also proved to be a factor in the stability of the suture-tendon construct, in the group 2, the tendon stumps were subjected to suture tying from distal to proximal to the rupture zone, where we conjecture that the tension on the suture is more uniform and therefore, when subjected to stress force, it is distributed more evenly among the three suture threads giving more predictability to the system. This probably does not occur when the suture is tied in the reverse direction, presenting a stepped suture failure until final failure. We should consider that the type of failure in tendon repair is related to the characteristics of the injured tendon, the tension of the multiple ties, and the resistance to tensile force of the construct. Therefore, we consider that prior to the failure of the repair, there is elongation of the construct, which leads to elongation of the tendon and is likely the (*in vivo*) factor for the loss of strength of the repaired tendon.

The suture of Group 3 showed a slightly higher value of tensile strength compared to Group 2, but without statistical significance, demonstrating that both sutures are equally safe. This data may have some significance when analyzing the factors of tensile strength and type of failure together. Group 1, with the lowest ULF, all suture failures occurred due to suture breakage, while in group 2, with an increase in tensile strength, five tendons out of 12 occurred suture pull-out, and in group 3, where we obtained the highest ULF values, three suture pull-outs out of 12 occurred. Considering that calcaneal tendon injuries are usually chronic with tendon stretching, we can hypothesize that there is a direct relationship between a significant increase in suture resistance and the probability of tendon avulsion. This fact only occurred in the specimens of Groups 2 and 3, and all avulsions occurred in the distal stump, a factor that we relate to its shorter length and therefore a smaller longitudinal area for suture crossing and anchoring.

The cross-stitch sutures promote stable anchoring to the body of the injured tendon and cause less damage to the extratendinous tendon vasculature. They also promote a less inflammatory process with a shorter duration, and the knots are made intratendinous, all of which contribute to the healing of the injured tendon and reduce the time for possible compression on the sural nerve during the suturing process. In addition, we found that the stiffness data in group 2 were more homogeneous, probably due to simultaneous suture tension and also resulting in greater tension on the distal stump, requiring initial equinus immobilization during the repair period for the rupture, but allowing for early loading due to the resistance of the construct. Furthermore, the more even distribution between suture rupture and tendon pullout in group 2 suggests that a more rigid system may provide better distribution of intramural forces when performed from distal to proximal. In this way, we suggest that the triple shoelace technique with absorbable thread and the group 2 suture provide greater stability to the construct with a lower probability of suture failure and tendon detachment, resulting in secure suturing and early return to activities when applied *in vivo*, but further studies are needed.

Limitation

The first limitation of our study, we cite the use of a bovine model. Despite being similar, there are subtle differences in the histology, texture, and bioconfiguration of the bovine Achilles tendon compared to the human Achilles tendon. However, they are similar in their macro morphology and allow sample homogeneity, and several other studies have already validated these tests performed in different animal models [13,16,17]. For the study, as the tendons were chosen randomly, the dimensions of the tendons could be a bias in the biomechanical test results. The dimensions of bovine tendons in our study in the three groups showed approximate measurements and did not present a significant difference between the groups. We found similarity to the observations in the work of Wang et al [16], who studied 40 fresh bovine tendons in their analysis. The similarity of the dimensions of the tendons

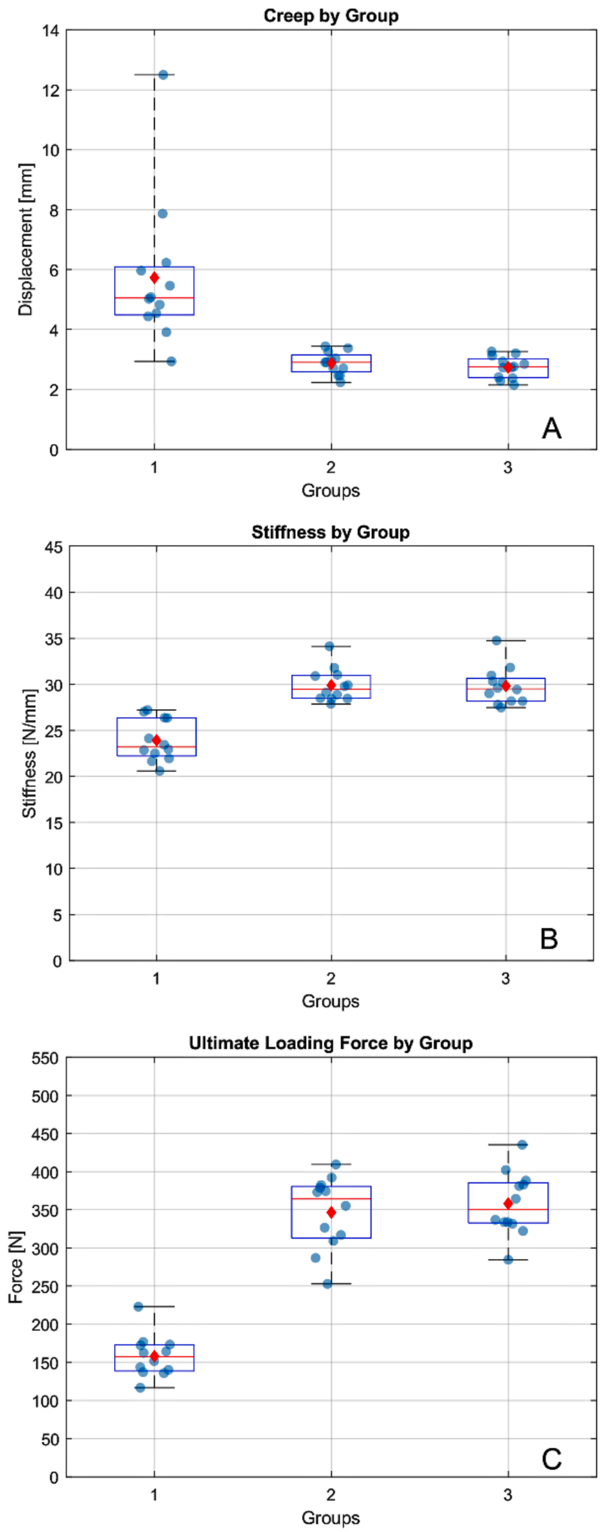

Fig. 3. Boxplot displaying the creep in the tendon suture during the constant load phase of 50 N for 300 s (A). Distribution by groups of the stiffness of sutured tendons, recorded in Newtons per millimeter (B). Distribution of the ultimate load force required for suture system failure, separated by groups (C). On the box, the central horizontal line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points. The diamond shaped dot represents the mean value and the spherical dots represent each data point.

Table 2
Mean and standard deviation (SD) values of the biomechanical data for creep, system stiffness, and ultimate load force of the test specimens.

Group	Creep Mean [mm]	SD [mm]	System Stiffness Mean [N/mm]	SD [N/mm]	ULF Mean [N]	SD [N]
1 (n = 12)	5.9	2.5	23.2	2.8	158.2	27.5
2 (n = 12)	3.0	0.4	30.3	1.1	346.5	47.6
3 (n = 12)	2.9	0.4	29.8	2.3	358.1	41.6

Table 3
Distribution of failure mode across all groups.

Failure mode	Group		
	Group 1	Group 2	Group 3
Suture breakage	11	7	9
Suture pull-out	1	5	3

Table 4
p-value for statistical tests between groups. We found statistical significance in the comparative tests between groups 1-2 and 1-3 in terms of means of creep, system stiffness and maximum system strength. There was no statistically significant difference between means in group 2 and 3 when analyzing creep, system stiffness and ULF.

Groups Being Tested	Creep F-test	*t*-test	System Stiffness F-test	*t*-test	ULF F-test	*t*-test
1–2	≈0	0,0038	0,48	≈0	0,1494	≈0
1–3	≈0	0,0025	0,5357	≈0	0,3588	≈0
2–3	0.5976	0.2655	0.1751	0.4108	0.5826	0.2286

Table 5
Fischer Exact Test p-values for the tests between groups. We found no statistical significance in the comparative tests meaning that there is no statistically significant association between groups and failure mode.

Groups Being Tested	Fischer Exact Test *p*-value
1–2	0.1550
1–3	0.5901
2–3	0.6668

studied demonstrates that this was not a relevant factor in the differences found in resistance, the final resulting maximum force, and the type of failure between the studied groups.

Other limitations rely on some biases that may have influenced our results, such as the lack of histological study of the anatomical specimens, the failure to measure the contact pressure at the ends of the stumps produced by the sutures to evaluate the contact and shortening produced by compression on the stumps, and the failure to measure the tension force individually for each pair of sutures. This measurement could be useful to determine the sequence of system failure and to understand the direction of the ties for comparison between shoelace and traditional techniques. The next step is to expand this study to include these features.

Conclusion

In conclusion, the results show that the addition of three absorbable suture threads significantly reduced creep in the preloading phase and increased the stiffness and ultimate load force up until rupture, demonstrating that the technique is feasible for repair and allows for earlier postoperative rehabilitation. The order of suture knots in the triple shoelace technique did not show statistical significance in terms of the ultimate load force of the system, creep or the stiffness of the system, but for this last biomechanical variable, group 2 with suturing going from distal to proximal at the stump tip reaches a better distribution of tension in all threads, promoting a marginal improvement in the suture tendon construct.

Declaration of Competing Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

[1] Wallace RGH, Heyes GJ, Michael ALR. The non-operative functional management of patients with a rupture of the tendon Achillis leads to low rates of re-rupture. J Bone Joint Surg [Br] 2011;93-B(10):1362–6.

[2] Keating JF, Will EM. Operative versus non-operative treatment of acute rupture of tendon Achillis: a prospective randomised evaluation of functional outcome. J Bone Joint Surg [Br] 2011;93-B:1071–8.

[3] Kearney RS, Costa ML. Current concepts in the rehabilitation of an acute rupture of the tendon Achillis. J Bone Joint Surg [Br] 2012;94-B:28–31.

[4] O'Brien M. The anatomy of the Achilles tendon. Foot Ankle Clin 2005;10(2):225–38.

[5] Doral MN, Alam M, Bozkurt M, Turhan E, Atay OA, Dönmez G, et al. Functional anatomy of the Achilles tendon. Knee Surg Sports Traumatol Arthrosc 2010;18(5):638–43.

[6] Heitman DE, Ng N, 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.

[7] Aslan M, Büyükkurt MC, Yildirim Ü. Comparison of different absorbable suture materials in skin closure: an experimental study in rats. Pain Clinic 2005;17(1):81–8.

[8] Yanqing H, Hai J, Qi L, Jian L, Xin T. Biomechanical study of different suture methods in repairing tendon rupture. Chinese J Repar Reconstruct Surg 2013;31(10):1208–13.

[9] Polykandriotis E, Ruppe F, Niederkorn M, Polykandriotis E, Bräuer L, Horch RE, et al. Polytetrafluoroethylene (PTFE) suture vs fiberwire and polypropylene in flexor tendon repair. Arch Orthop Trauma Surg 2021;141(9):1609–14.

[10] 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 2020;109:110574.

[11] Medeiros AC, Araújo-filho I, Carvalho MDF. Fios de sutura. J Surg Clinic Res 2016;7(2):74–86.

[12] Devries JG, Scharer BM, Summerhays BJ. Acute Achilles rupture percutaneous repair. Clin Podiatr Med Surg 2017;34(2):251–62.

[13] 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. J Bone Joint Surg [Br] 2012;94-B(5):663–7.

[14] Wagner P, Wagner E, Lopez M, Etchevers G, Valencia O, Guzman-Venegas R. Proximal and distal failure site analysis in percutaneous Achilles tendon rupture repair. Foot Ankle Orthop 2019;4(4):2473011419S00043.

[15] 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.

[16] 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.

[17] 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 2019;51:559–64.

[18] Nyström B, Holmlund D. Separation of tendon ends after suture of Achilles tendon. Acta Orthop Scand 1983;54(4):620–1.

[19] 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.

[20] 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):251–7.

[21] 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.