Jigless knotless internal brace versus other open Achilles tendon repair under progressive rehabilitation protocol: A biomechanical study

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Research Article

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Abstract

Background

The jigless knotless internal brace surgery (JKIB), a modified minimal invasive surgery (MIS) for acute Achilles tendon injury, showed the advantage of sural-nerve injury prevention in MIS and superficial wound infection in open surgery in previous clinical research. However, to date, biomechanical testing remains not yet validated.

Materials and methods

Sixty porcine fresh Achilles tendons were used to compare the JKIB with other open surgery techniques, the four-strand Krackow suture (4sK) and triple-buddle suture (TBS) in biomechanic testing with cyclic loading at 1 Hz. This approach simulated a progressive rehabilitation protocol where 20-100N was applied in the first 1000 cycles, followed by 20-190N in the second 1000 cycles, and then 20-369N in the third 1000 cycles. The cycles to the repair gap 2mm, 5mm and 10mm were recorded. The survival cycles was defined as repair gap achieving 10mm.

Results

With respect to survived cycles, a significant difference was found among the three groups, in which the TBS was the most robust, followed by the JKIB and the 4sK, with mean survived cycles were 2639.3 +/- 263.55, 2073.6 +/- 319.92 and 1425.25 +/- 268.96, respectively. Significant difference was defined via a post hoc analysis with the Mann–Whitney U test after the Bonferroni correction ($p < 0.017$).

Conclusions

The TBS was the strongest suture structure in acute Achilles tendon repair. However, the JKIB could be an option in acute Achilles tendon repair with the MIS technique due to it being more robust than the 4sK, which has been favored in open repair.

Introduction

The Achilles tendon, which is the strongest tendon in human body, is involved in much of daily life activities. Unfortunately, it is a frequently ruptured major tendon, and the incidence is higher in middle-aged men, especially during recreational sports [1–5]. For active young athletes, the surgical repair of ruptured Achilles tendon was benefit in ankle early mobilization, which improving outcomes due to better muscular tendinous tropism, well collagen alignment, and preventing scar adhesions and muscle atrophy [6–9].

There are several operative option in Achilles repair, including open repair with or without augmentation, percutaneous repair, and minimally invasive surgery (MIS). When comparing the outcome between MIS and open surgery, no significant differences was noted in the rate of re-rupture, deep infection, tissue adhesion, or nerve injury from the report of one high-quality meta-analysis [10]. However, MIS has been reported as having better subjective outcomes, cosmetic appearance and a significantly lower rate of superficial infection and wound healing complications [10]. Although a number of MIS methods have been developed over the years, recent efforts have advanced the technique of mini-open or the MIS methods [11–22]. Kakiuchi et al. were the first to describe the combination method of mini-open and the percutaneous technique over two decades ago [18]. Kakiuchi's method has since been modified in several ways, with simpler suture techniques under more complex repair tools having been developed [11, 13, 16, 22]. However, increased risk of iatrogenic sural nerve injuries in mini-open or MIS techniques have been reported [15, 20, 23–27].

According to a cadaver study, surgeons can decrease the risk of iatrogenic sural nerve injury by conducting all percutaneous suturing within 8 cm proximal to the calcaneal tuberosity [28]. The aforementioned study reported that the Achilles tendon lateral border crossing site of the sural nerve was about 8- to 10- cm above the calcaneus tuberocity in most cases [28]. In response, the"jigless knotless internal brace technique" (JKIB) was developed which could perform in minimal invasive fashion without the risk of iatrogenic superficial sural nerve injury [19]. Although the clinical outcome of the case series was well, the suture strength has not yet been validated. Accordingly, we chose the four-strand Krackow suture (4sK) for comparison since this suture is favored for open repair due to easily performed and well clinical outcome and in previous publication [29]. In addition, we chose the triple-bundle technique (TBS) as another suture for comparison because it was shown to be stronger than the 4sK suture in a biomechanical study [30]. The current study aimed to biomechanically compare the JKIB with other open-repair techniques in simulating the progressive rehabilitation program. We hypothesized that the biomechanical strength of the JKIB was not less than other two open repair method.

Materials And Methods

Sample Collection and Preparation

Sixty fresh porcine Achilles tendons were acquired from fresh adult male pigs (2 years in mean age). All specimens were stored in a − 20°C freezer and thawed to room temperature until experimental assessments. To prevent desiccation, all samples were wrapped in saline-soaked gauze when thawing. The samples were then divided evenly in the three surgical technique groups: (1) four strand Korackow (4sK) suture end to end open repair (Hi-Fi® Suture Conmed) (Fig. 1A); (2) triple-bundle suture technique (TBS) (Hi-Fi® Suture Conmed) (Fig. 1B); (3) jigless knotless internal brace technique (JKIB) (PopLok® Knotless Suture Anchors; Hi-Fi® Suture CONMED) (Fig. 1C).

Surgical procedure

All surgical procedures in all specimens were carried out by an orthopedic foot and ankle surgeon (PYK). An Achilles tendon rupture was created using a No. 10 scalpel and running the section perpendicular to the tendon fiber at 4 cm proximally from the calcaneal insertion center. Details of the surgical procedure are described below:

1. Four-stranded Krackow suture (4sK): The Krackow suture was conducted according to Krackow [31]. Three locking loops were placed 5 mm in each strand and at each end of the tendon with the Hi-Fi® Suture (Conmed). A 5 mm stitch interval was chosen because stitch intervals of 5.0 mm were found to have significantly smaller elongation compared with other longer stitch intervals after cyclic loading [32]. The loops were tightened to obtain end-to-end repair after three surgeon's knots were tied (Fig. 1A).
2. Triple-bundle suture technique (TBS): Each bundle was located in the lateral portion of the tendon and composed of three cross loops at the proximal end and two cross loops tightened with three surgeon's knots at the distal end. The bundle located in the central portion of the tendon was composed of three cross loops at the distal end and two cross loops tightened with three surgeon's knots at the proximal end. The Hi-Fi® Suture (Conmed) was used in the triple-bundle suture technique (Fig. 1B).
3. Jigless knotless internal brace technique (JKIB): The JKIB was conducted as our previous report [19]. Krackow sutures were applied at the proximal stump, as described above. The percutaneous suture with the Hi-Fi® Suture (Conmed) was crisscrossed through the distal stump. The end of the distal-stump suture was looped through the Krackow locking loop at the proximal stump. The ipsilateral Krackow sutures and the contralateral crisscrossed sutures were seated at the calcaneal tuberosity with two 4.5mm PopLok® Knotless Suture Anchors (Conmed) (Fig. 1C).

Biomechanical testing

Each calcaneus of the repaired Achilles tendon was fixed horizontally in a custom-made adjustable fixture at the base of a dynamic tensile testing machine (MTS Bionix® Servohydraulic Test Systems, Technology Drive Eden Prairie, MN USA) (Fig. 2). The tendon end 3 cm above of the repair site was rigidly secured by the custom made steel clamp attached to the testing machine actuator. Each specimen was tested to measure the elongation amount occurred at every cyclic loads, as well as the ultimate load to complete failure. Above data were collected by the hydraulic biomechanical load cell then conducted with the analog-to-digital data output to a host computer. To simulate a progressive rehabilitation program, as suggested by Lee, S. J. et al. and Demetracopoulos, C. A. et al., the tested loading protocol with 3000 cycle totally at 1Hz was composed of three cyclic-loading stages of 1000 cycles: (1) 20–100 N; (2) 20–190 N; and (3) 20-369N [22, 33]. The cycles to the repair gap 2-mm, 5-mm and 10-mm were recorded. The gap was documented during cyclic loading test using linear variable differential transformer (Parker Hannifin Corporation model S-LVDT-24, range 12.0-mm, Williston, VT). The tested cyclic-loading values represented the force through the tendon during a passive ankle-dorsiflexion stretch (20–100 N), weight-bearing ambulation with a cam under a 1-inch heel lift shoe (20–190 N) and without a cam (20-369N)

[34, 35]. Failure of the repair was defined either as repair gap over 10mm. Thus, the survival cycles was defined as the number of cycle achieving 10mm in repair gap.

Statistical Analysis

To determine the sample size, a pilot study was performed based on elongations after cyclic loading, for which 15 specimens were randomly assigned to three groups (4sK, TBS, and JKIB). The effect size was calculated as 0.53 after the pilot study. Then, a total specimen number of 60 was determined after $\alpha = 0.05$, a power ($1-\beta$) of 0.80, and f of 0.53 were set under the G power, ver. 3.1.3 (http://www.gpower.hhu.de; Heinrich Heine-University of Dusseldorf, Dusseldorf, Germany). All data collected from the biomechanical loading cell, elongation, and failure load were exported to SPSS, version 17.0 (SPSS Inc, Chicago, IL, USA) for statistical comparison.

Cycles to the determined repair gap among the three groups were compared using the Kruskal– Wallis test. $P < 0.05$ was set as statistical significance. Post hoc analysis was conducted with the Mann–Whitney U-test which the significance difference was set as $p < 0.017$ after Bonferroni correction.

Results

Survived cycles

The survived cycles was defined as the repair gap achieving 10-mm in this research. All repairs survived in the first stage, the cyclic loading from 20 to 100 N during biomechanical testing, and no repairs survived in all three stages of the cyclic loading. There was significance in survival cycles between the groups after the post-hoc analysis ($p < 0.001$) (Fig. 3). The mean survived cycles in TBS, 4sK, and JKIB were 2639.3 +/- 263.55, 2073.6 +/- 319.92 and 1425.25 +/- 268.96, respectively (Fig. 3). The median and range of the survived cycles in TBS, 4sK, and JKIB were 1384.5 (1003–1875), 2712.5 (1901–2953), and 2062.5 (1504–2741), respectively (Fig. 4).

Number of cycles to the repair gap

Kruskal-Wallis testing showed there was significant difference in three treatment group when comparing the measurement (number of cycles to 2-mm repair gap and 5-mm repair gap) ($P < 0.001$) (Fig. 3). Post hoc testing (Mann-Whitney) revealed that in all measurement, the TBS was most durable followed by JKIB and 4Sk ($P < 0.001$) (Fig. 3). Besides, the 4sK was weakest ($P < 0.001$) (Fig. 3).

Failure mode

All failure mechanisms in the 4sK group were due to suture breakage. Meanwhile, the failure mechanisms of the TBS included 14 specimens tearing at the tendon-suture interface, and 6 specimens undergoing suture breakage. In the JKIB group, all specimens failed due to tears in the proximal stump tendon-suture interface.

Discussion

The present result in this cyclic loading test showed the triple-bundle suture technique (TBS) was the significantly strongest suture structure followed by the Jigless knotless internal brace technique (JKIB). The four-stranded Krachow suture (4sK) was significantly weaker than other two group. In the three groups, the JKIB could be performed in minimal invasive technique, and showed well clinical result in previous study [19].

Although numerous biomechanical studies of Achilles tendon repair have been published over the past three decades, controversy remains regarding the different suturing techniques [22, 30, 33, 36–40]. In particular, elongation after post-surgical rehabilitation is a concern, and there is also no consensus in suturing technique under the simulated rehabilitation protocols in biomechanical studies [33, 36, 41]. The biomechanical strength of the JKIB which could be performed in minimal invasive fashion was not validated in previous research [19]. In response, we used animal simulated-progressive rehabilitation protocols to biomechanically study to evaluate the repair strength of the JKIB.

Recently, several research had discussed about how much of the Achilles tendon elongation is clinically significant, but there was still no consensus [42–46]. In our research, we defined the failure of the cyclic loading test as the repair gap achieving 10-mm which were also defined as biomechanical failure in the previous research [22, 33]. Besides, previous research showed that the repair gap over 5-mm wound lead to weakness in plantar flexion [45, 46]. All specimens were survived in the 20-100N cyclic loading. Thus, it is reasonable early ankle passive range of motion exercise which was verified by recent clinical meta-analysis study [47, 48]. The result showed the JKIB was stronger than 4sK, but there was still risk in failed repair when weight-bearing ambulation with a cam under a 1-inch heel lift shoe due to some specimen not survived in the 20-190N cyclic loading.

The greater strength of the JKIB over the 4sK could be due to the difference of suture fixating. The suture fixating of the JKIB was knotless anchor seat over the calcaneus not the end to end knot tied of the 4sK. The result was similar to the research of Clanton, T. O. et al which compared the percutaneous Achilles repair system (PARS), and SpeedBridge (SB) repairs [41]. The found the SB repair was stronger than PARS repair in cyclic loading test. Although the suture configuration were all the same in proximal stump in PARS and SB, the suture was seat at calcaneus by the knotless anchor in the SB while the suture was end to end tied in PARS [41]. Furthermore, the present study showed the failure mode of the JKIB was tear in the proximal stump tendon-suture interface with anchor remained grossly intact, but all of the 4sK was failed in the suture breakage. This finding showed the suture fixating was stronger in knotless anchor used in JKIB.

An additional factor that JKIB was stronger than 4sK is the strand crossing the repair site. Although there was only two strand Krachow suture in the proximal stump of JKIB, the looped percutaneous suture of distal stump increased the numbers of strand crossing the repair site in JKIB to six. Biomechanically, the number of strand between each group should be constant to made the result valid, but the four strand end to end Krachow suture is still the benchmark in Achilles open repair clinically [6, 9, 29, 36, 37]. Thus, it was still reasonable that the 4Sk was chosen as comparison.

There are several limitations in this work. First, as with other biomechanical studies, this study only offered the time-zero biomechanical representation of each Achilles repair technique. Clinically, the rehabilitation program would be more aggressive over time as increased loading during tendon healing.

Second, the study was conducted on porcine Achilles tendons, not the cadaveric tendons; however, porcine tendon has been adopted in numerous biomechanical works to evaluate the varied tendon repair methods or fixation techniques in tendon grafts [32, 49]. Besides, we found a similar trend in our comparisons between the 4sK and TBS as well as similar survival cycles for the 4sK as in previous studies [30, 33]. According the finding of Jaakkola et al., the load to failure of the TBS was significantly larger than the 4sK [30]. In our study, we chose cyclic loading as the measure parameter for simulation of the clinical rehabilitation protocol. The TBS was significantly larger than the 4sK in the number of cycles to 2-mm, 5-mm, and 10-mm repair gap. Furthermore, Lee et al. had performed the cyclic loading test to compare the 4sK with and without augmented with epitendinous suture [33]. They found the all of the 4sK without augment survived the 20-100N cyclic loading, yet none survived in the whole cycle of the 20-190N cyclic loading which as the same in this study [33].

In the failure model, the result of the JKIB and 4sK in our animal biomechanical work was similar with cadaveric studies performed by Cox J. T. et al, Heitman et al., and Huffard et al. [36, 37, 50]. Cox J. T. at al analyzed the mechanical strength of knotted and knotless suture bridge repair of the Achilles tendon insertion and the result showed all specimens were failed in the tendon-suture interface which was the same in the failure mode of JKIB in this study [50]. Although the suture structure of the JKIB was differed from the suture bridge in Achilles tendon insertion repair, there were knotless anchor seat in the calcaneus when performing JKIB or suture bridge. The 4sK in our work primarily failed due to suture breakage, which is comparable to Heitman et al. and Huffard et al. [36, 37]. The TBS in our work torn primarily at the tendon-suture interface while Jaakkola et al. showed the most specimens of TBS torn at the tendon clamp [30]. The difference of the failure mode in TBS might be due to the difference of biomechanical protocol which Jaakkola et al. performed the load to failure, not the cyclic loading test. For above, we believe the results are still valid.

In conclusion, the results presented in this study showed that the JKIB was more endurable than the 4sK in cyclic-loading tests that simulated progressive rehabilitation protocol. The TBS was the most robust and strongest of the three groups in terms of survival cycles. The JKIB can be easily performed in MIS without a suture jig and showed acceptable one-year follow-up clinical outcomes in previous clinical research. According to the above, the JKIB could be considered another treatment option in acute Achilles-tendon rupture.

Declarations

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Ethics approval and consent to participate: Not applicable due to usage of *cadaveric porcine Achilles tendon,* not living animals.

Consent for publication: Not applicable

Availability of data and materials: The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests

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Author Contributions:

Conceived and designed the study: PYK, FCS

Performed the study: PYK

Analyzed the data: PYK, CHH, CKH, MTH, IMJ, WRS, PTW, FCS

Contributed reagents/materials/analysis tools: CHH, CKH, IMJ, WRS, PTW, FCS

Wrote the manuscript: PYK, FCS

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Figures

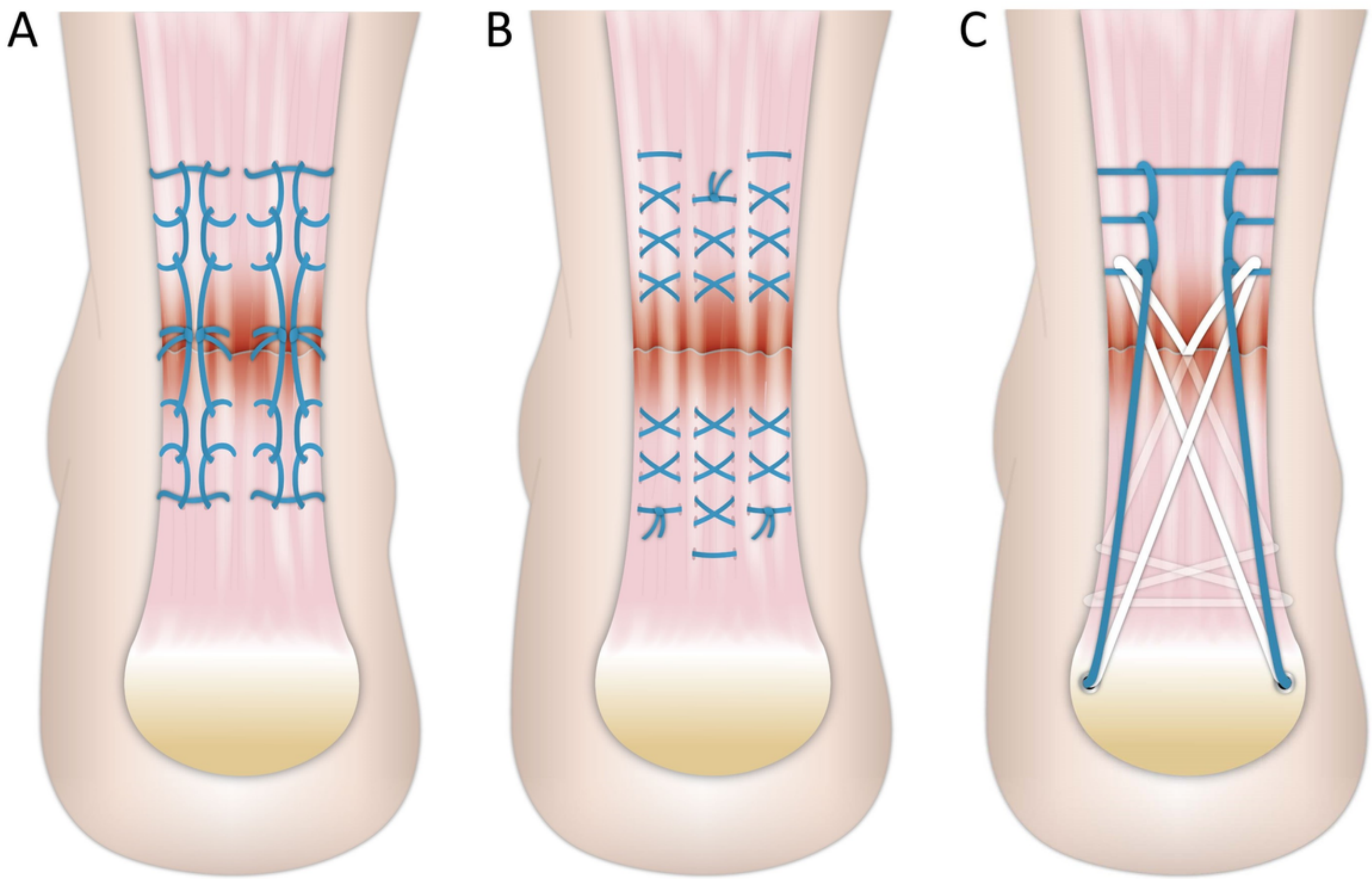


Figure 1

Schematic diagram of the four-stranded Krachow suture repair (4sK) (Fig. 1A); triple bundle suture technique (TBS) (Fig. 1B); and jigless knotless internal brace technique (JKIB) (Fig. 1C).

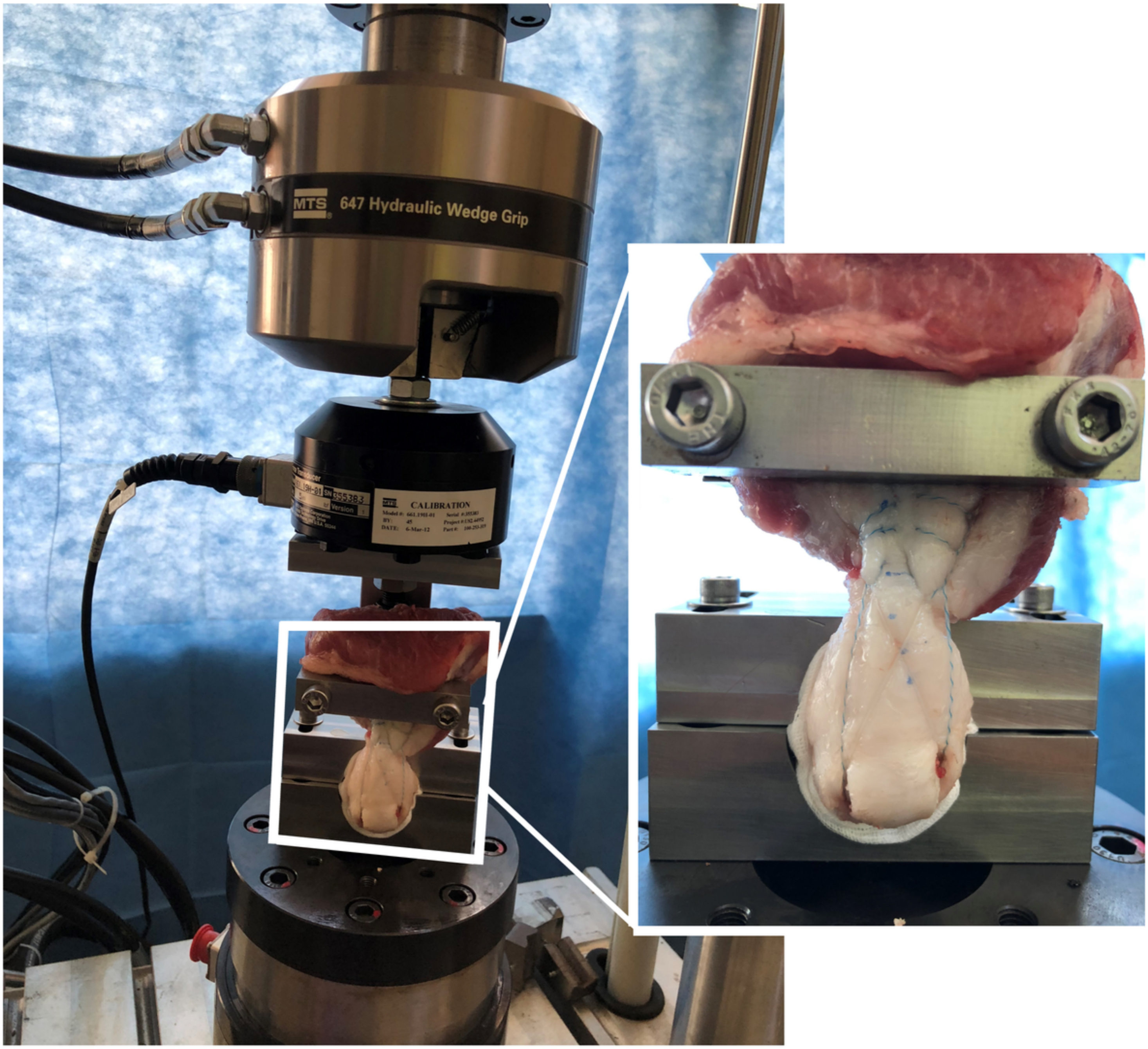
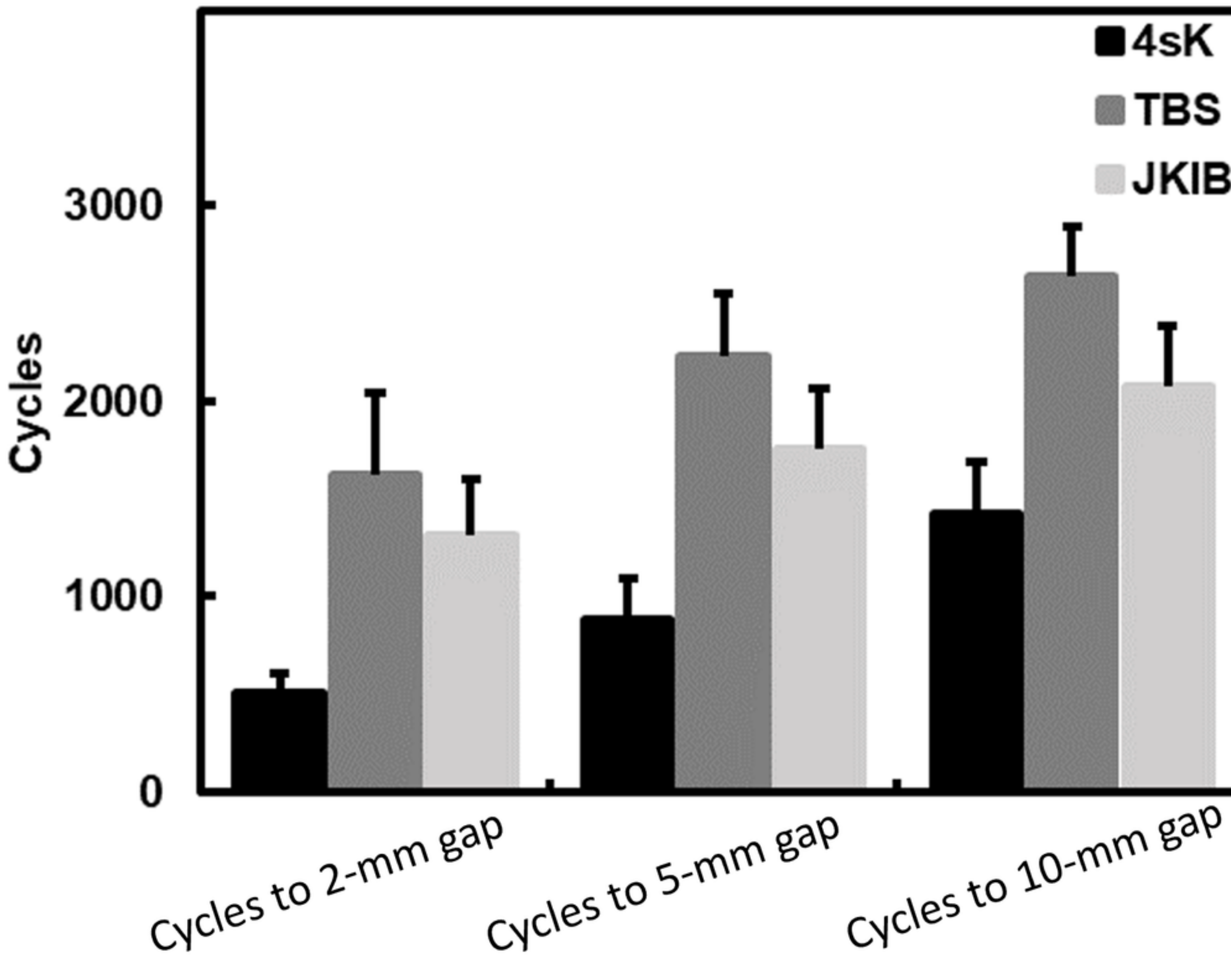


Figure 2

The repaired Achilles tendon was anatomically oriented fixed in a dynamic tensile-testing machine.



	4sK	TBS	JKIB
Cycles to 2-mm gap	512.3 +/-98.2	1624.6 +/- 427.4	1316.3 +/- 289.7
Cycles to 5-mm gap	885.1 +/- 210.0	2234.9 +/- 325.4	1753.5 +/-318.4
Cycles to 10-mm gap	2639.3 +/- 263.55	2073.6 +/- 319.92	1425.25 +/- 268.96

Figure 3

The cycles to the repair gap of 2-mm, 5-mm, and 10-mm for the Achillon repair in four-stranded Krachow suture repair (4sK), triple bundle suture technique (TBS), and jigless knotless internal brace technique (JKIB). Post hoc testing (Mann-Whitney) revealed that the TBS was most durable followed by JKIB and 4Sk in all measurement ($P<0.001$). Besides, the 4sK was weakest ($P<0.001$).

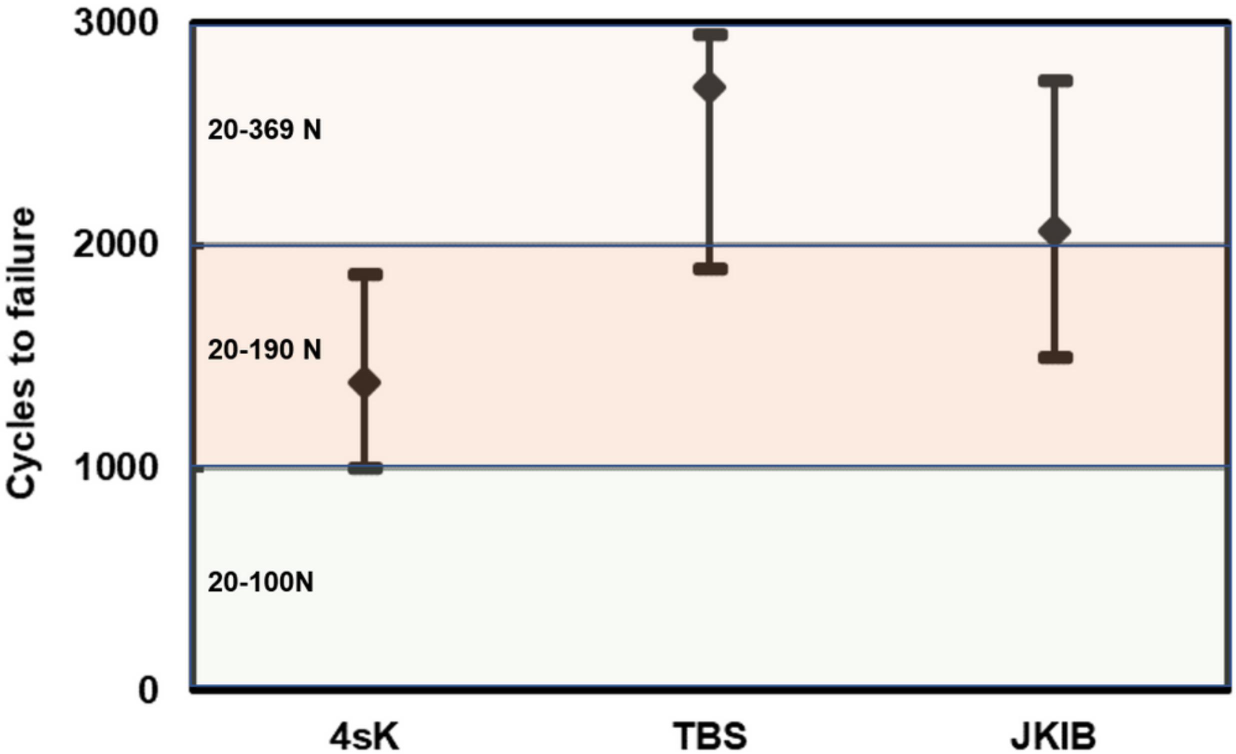


Figure 4

Median (diamond mark) and range (error bars) for survived cycles of the three different repair techniques. The loading amount was noted for the three different cyclic loading stages. The mean (range) of four-stranded Krachow suture repair (4sK), triple bundle suture technique (TBS), and jigless knotless internal brace technique (JKIB) was 1384.5 (1003-1875), 2712.5 (1901-2953), and 2062.5 (1504-2741) respectively. There was significance in survival cycles between the groups after post-hoc analysis ($p<0.001$).