Original Article

Biomechanical Comparison of Transosseous Four-strand Tendon Suture Patterns for Repair of Ruptured Distal Common Calcaneal Tendon: An *Ex Vivo* Study in Dogs

Tae-Hwan Ahn[1] Min-Yeong Lee[1] Jaekyoung Lee[1] Hwi-Yool Kim[1*]

Abstract

There is no golden standard method of suturing for distal common calcaneal tendon rupture in dogs. Thus this study aimed to evaluate and compare the mechanical characteristics of three distinct transosseous suture (TOS) repair techniques, which were specifically developed to treat ruptured distal common calcaneal tendons and to identify golden standard suturing method. The study was performed using 30 hind limbs obtained from 15 canine cadavers with weights ranging between 7.9 kg and 11.4 kg. The repair methods using modified Becker suture (group 1), modified Krackow suture (group 2), and modified double-Tsuge suture (group 3) were randomly assigned. Each group contained 10 samples. Each repair technique was used, and all the samples were fixed on a wooden board at an angle of 135 ^{o}. Mechanical tests were performed by applying tension, and the loads at gap formations of 1, 2, and 3 mm, as well as the load at the time of failure, were measured. Group 1 had significantly higher strength than groups 2 and 3 in all three displacement criteria (1, 2, and 3 mm) with a p-value less than 0.05. The mean maximum failure load was significantly high in group 1 (133.0 ± 8.5 N) followed by group 2 (128.1 ± 11.8 N), and then, group 3 (88.3 ± 10.9). Therefore, in terms of clinical outcomes and dynamic biomechanical properties related to tendon healing, the modified Becker suture is the most effective method among TOS repairs for treating distal common calcaneal tendon rupture in dogs.

Keywords: dog, common calcaneal tendon, transosseous suture, modified Becker suture, modified Krackow suture, modified double-Tsuge suture

[1]*Department of Veterinary Surgery, College of Veterinary Medicine, Konkuk University, Seoul 143-701, Republic of Korea*
***Correspondence**: hykim@konkuk.ac.kr* (H.Y. Kim)

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Introduction

The Achilles tendon, also known as the common calcaneal tendon, is formed by structures attached to the tuber calcanei of the foot. Its main components include the tendons of the flexor digitorum superficialis and gastrocnemius muscles, along with contributions from the biceps femoris, semitendinosus, and gracilis muscles. Fibers from the biceps femoris strand help form the Achilles tendon and attach to the medial lip of the femur's back surface. Dense connective tissue fibers from the interfascicular septa of the biceps femoris join the tendon, creating a single functional unit without the need for muscle fiber attachment (Evans and Lahunta, 2012). Common calcaneal tendon damage can manifest in two ways (Wilson *et al*., 2014; Tobias and Johnston, 2012; Fahie, 2005). The first scenario involves a rupture or laceration of one or more common calcaneal tendon components due to excessive external force or direct trauma (Wilson *et al*., 2014; Tobias and Johnston, 2012; Fahie, 2005). The second scenario involves a chronic avulsion injury at the gastrocnemius tendon insertion site, which is believed to result from a degenerative condition (Wilson *et al*., 2014; Tobias and Johnston, 2012; Fahie, 2005). Irrespective of the type of injury, surgical fixation of the torn tendon is essential to achieve the best possible result (Wilson *et al*., 2014; Tobias and Johnston, 2012; Fahie, 2005).

In dogs, rupture of the common calcaneal tendon is the second most common tendon rupture after the proximal bicep tendon rupture (Jopp and Reese, 2009). The frequencies of injury to the common calcaneal tendon in dogs are as follows: tendino-osseous insertion (77%), tendon body (12.5%), and myotendinous junction (10.5%) (Gamble *et al*., 2017). The distal region of the gastrocnemius and superficial digital flexor tendon have decreased tensile strength owing to the presence of multiple low vascularized fibrocartilaginous areas, in contrast to the regular parallel-fibered areas in the proximal tendon regions (Jopp and Reese, 2009). Therefore, when a rupture occurs in the distal part of the common calcaneal tendon, an ideal suture technique that can provide sufficient tension, resist gap formation, and minimally affect the tendon vascular supply is required.

Owing to the increased risk of slow healing and subsequent failure of tendons with a anastomotic gap greater than 3-mm, any suture pattern used for canine tendon repair must be able to withstand the formation of such a gap under physiological loads (Wilson *et al*., 2014). The linear arrangement of collagen bundles in tendons imparts limited holding power to standard sutures, thereby establishing the need for multiple specialized suture patterns for the re-apposition of tendon to tendon or tendon to bone (Wilson *et al*., 2014; Wu and Tang, 2014). The following suture techniques are appropriate for flat tendons and have adequate strength and satisfactory functional outcomes: modified Becker suture, modified Krackow suture, and modified double-Tsuge suture (Angeles *et al*., 2002; Wilson *et al*., 2014).

To the best of our knowledge, no biomechanical assessments of these repair techniques for distal common calcaneal tendons have been reported. This study aimed to compare the biomechanical characteristics of three suture techniques specifically developed for a ruptured distal common calcaneal tendon and to establish an effective treatment option for use in these scenarios. In this study, we used three different four-stranded suture patterns: modified Becker suture (Group 1), modified Krackow suture (Group 2), and modified double-Tsuge suture (Group 3). The results of this study can contribute to finding a suturing method that can be utilized as a golden standard for distal common calcaneal tendon rupture. Furthermore, considering the characteristics of different suturing methods, this study can provide criteria for selecting an efficient suturing technique.

.Materials and Methods

Cadaver collection: Thirty pelvic limbs were collected from 15 adult dogs. The mean weights of the canine cadavers were 10.2 kg (7.9–11.4 kg). The cadavers used in the experiment were found to have no evidence of musculoskeletal diseases in their hind limbs through orthopedic examination, and all were euthanized for reasons unrelated to the study. The cadavers were stored at -70℃ and only thawed at room temperature when to be sampled and tested. After collection, the limbs were subjected to sampling and surgical procedure without delay. The samples were then covered individually with saline-soaked gauze and refrigerated at 0℃ until they were tested on the same day.

Cadaveric hindlimb harvest and preparation: The soft tissue of the specimens, except for the calcaneal tendon, were removed, and the calcaneus was disarticulated from the tibia and fibula. The proximal portion of the common calcaneal tendon was excised at the point where the muscle ended and the tendon began (Fig. 1).

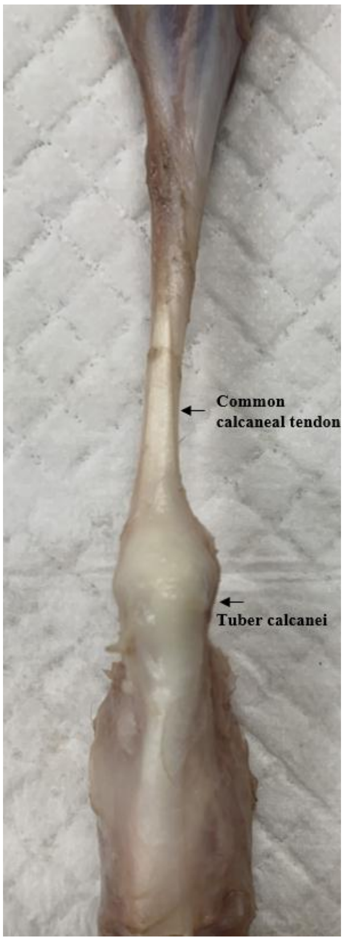

Figure 1 A photograph of the specimen after the preparation procedure. The calcaneal bone was disarticulated from the tibia and fibula, and the surrounding muscles and soft tissues were removed. The common calcaneal tendon was cut at the point where the tendon ended and the muscle began.

Surgical procedure: Using a randomization software (http://www.randomizer.org, Randomizer), the specimens were allocated to three treatment groups (n = 10 per group). A No. 10 scalpel blade was used to perform transection at the proximal dorsal surface of the tuber calcanei, which is the insertion site of the common calcaneal tendon. All suturing was performed in accordance with established guidelines, including the distance between the sutures, tension, and knot diameter, around all surgical incisions following transection. The suture material used was #2-0 Fiberwire (Arthrex Inc., Munich, Bavaria, Germany). Two 1.2 mm bone tunnels were created in a straight line from the insertion site of the common calcaneal tendon to the distal aspect of the calcaneal tuberosities, using a 1.2 mm K - wire for drilling. Sutures were threaded separately through each bone tunnel. Prior to tying the knot, the cut ends of the tendon were brought together to prevent the overlapping of tissues at the repair site. The suture tie was secured to a 2–hole suture button (Arthrex Inc., Munich, Bavaria, Germany) to withstand stronger tension. A six-thrown square knot was used to tie the sutures, and the tags of the suture were cut 3 mm away from the knot.

Modified Becker suture: Group 1 was repaired using the modified Becker Suture technique (Jordan *et al*., 2015). The initial suture was placed 7 mm away from the repair site. Two sets of sutures were positioned in a crisscross pattern on the side, spaced 3.5 mm apart. For each set of crisscross sutures, three cross-locks were formed, with each cross-lock occupying 3.5 mm. After placing each crisscross suture, the suture was gently pulled until the surface of the tendon changed (Fig. 2A).

Modified Krackow suture: Group 2 was repaired using the modified Krackow Suture technique (Fig. 2B) (Ostrander *et al*., 2016). The sutures were positioned such that the transverse section of the tendon was divided into three parts. The initial Krackow suture was initiated by inserting the needle through the tendon substance up to 4 mm, followed by placing the first locking loop at 7 mm. Then, the second loop was placed at 14 mm, after which the suture was passed across the body of the tendon and repeated in the opposite direction. After flipping the tendon, for the second Krackow suture, the suture loops were inserted into the tendon slightly axial to the first suture, 10.5 mm and 17.5 mm away from the ends of the tendon. After each needle was passed through the tendon, the suture was pulled tightly to prevent loosening of the loop.

Modified double-Tsuge suture: Group 3 was repaired using the modified Tsuge Suture technique (Labana *et al*., 2001). Suture bites were taken 10 mm away from the repair site and passed longitudinally through the tendon, exiting from the core of the tendon (Fig. 2C). The suture ends were tied as previously described.

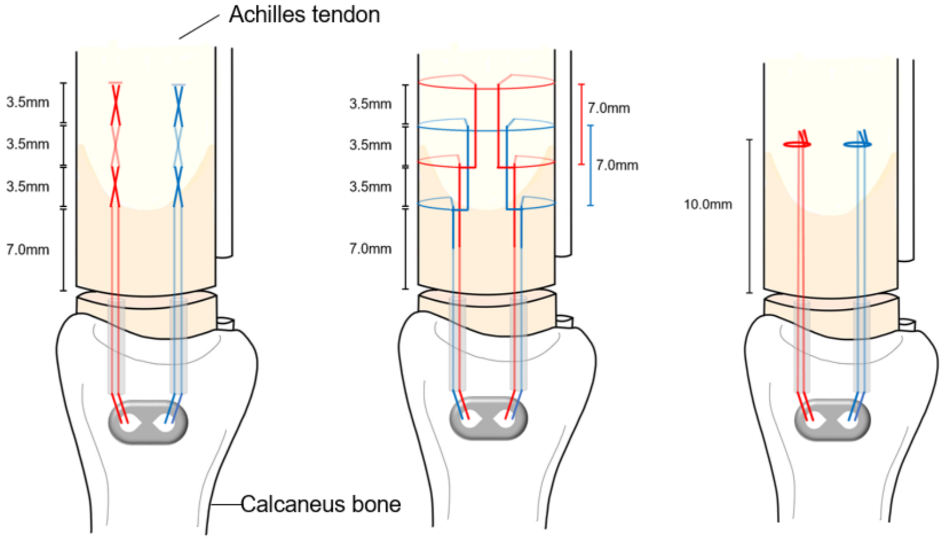

Figure 2 An illustration of the methods used for repairing ruptured common calcaneal tendon model(A) Modified Becker suture, (B) modified Krackow suture, and (C) modified double-Tsuge suture.

Biomechanical testing: All tendon repair models were laterally fixed to wooden boards by inserting two 1.5 mm screws into the calcaneus and tarsal bone, and the common calcaneal tendon was positioned at an angle of 135 ^{0} relative to the foot.

The tendon repair models were positioned on the experimental machine (INSTRON 4467; Instron®., Norwood, MA, USA). Tendon repair models fixed to wooden boards were secured to the bottom jig of the Instron machine, while the common calcaneal tendon was positioned on the top jig and firmly fixed in place with the jig (Fig. 3). The locking grips were connected to a 30-kN load cell, which was then attached to the crosshead of the experimental machine. Tendon repair models were initially preloaded to 1 N and subsequently subjected to a distraction force of 25 mm/min until failure without conducting any cycle tests. A surgical ruler was positioned directly next to the tendon repair model and within the video's field of view. The force required to achieve gaps of 1, 2, and 3 mm between the tendons was measured. Failure was defined as the point at which the maximum tension was reached or the suture broke or was pulled out, whichever occurred first.

Figure 3 A Photograph of tendon repair model.

Statistical analyses: Statistical analyses were conducted using SPSS Statistical Software (version 28.0.1.1, SPSS Inc., Chicago, IL, USA). The investigated parameters were 1 mm gap formation, 2 mm gap formation, 3 mm gap formation, maximum failure force (N), and mode of failure. The Shapiro–Wilk test was used for normality testing. The data obtained from the test were statistically analyzed using a one-way analysis of variance. When there was a significant difference among the data based on analysis of variance, post hoc Tukey tests were used to perform multiple comparisons. A P value of less than 0.05 was considered statistically significant. Graphs were created using GraphPad Prism 7 (GraphPad Software, San Diego, CA).

Results

Loads at 1 mm displacement: All three groups exhibited normality according to the Shapiro–Wilk test. The Shapiro-Wilk test is one of the statistical tests used to check for normality in data. It is used to determine whether a dataset follows a normal distribution. The mean loads at 1 mm displacement were 81.2 ± 8.0 N in group 1 (modified Becker suture), 36.8 ± 6.3 N in group 2 (modified Krackow suture), and 33.6 ± 9.0 N in group 3 (modified double-Tsuge suture) (Table. 1).

There was a significant difference (one-way of variance, $p < 0.05$) among the three groups. The results indicated that group 1 had a significantly higher mean load for producing a 1 mm gap than groups 2 and 3 ($p < 0.001$). However, the differences between groups 2 and 3 were not statistically significant (Fig. 4).

Loads at 2 mm displacement: The Shapiro–Wilk test indicated that normality was observed in all three groups. The mean loads at 2 mm displacement were 95.1 ± 5.5 N in group 1 (modified Becker suture), 59.5 ± 7.9 N in group 2 (modified Krackow suture), and 48.3 ± 10.4 N in group 3 (modified double-Tsuge suture) (Table. 1).

A significant difference was observed among the three groups ($p < 0.05$) as determined using a one-way analysis of variance. Group 1 required a significantly higher mean load to produce a 2 mm gap than groups 2 and 3 ($p < 0.001$). Additionally, the mean load required to produce a 2 mm gap was significantly higher in group 2 than in group 3 ($p = 0.013$) (Fig. 4).

Loads at 3 mm displacement: Normality was observed in all three groups based on the results of the Shapiro–Wilk test. At a 3 mm displacement, the average loads were 106.9 ± 6.6 N for group 1 (modified Becker suture), 80.0 ± 8.1 N for group 2 (modified Krackow suture), and 66.6 ± 10.4 N for group 3 (modified double-Tsuge suture) (Table. 1).

There was a significant difference ($p < 0.05$, One-way ANOVA) among the three groups. The mean load required to produce a 3 mm gap was significantly higher in group 1 than in groups 2 and 3 ($p < 0.001$). Additionally, the results indicated that the mean load needed to create a 3 mm gap was significantly higher in group 2 than in group 3 ($p = 0.004$) (Fig. 4).

Table 1 Loads at 1-, 2-, and 3-mm displacement.

Displacement distances	Load (N) at displacement		
	Group 1	Group 2	Group 3
1 mm	81.2±.8.0^{a}	36.8±6.3^{b}	33.6±9.0^{b}
2 mm	95.1±5.5a	59.5±7.9^{b}	48.3±10.4^{c}
3 mm	106.9±6.6^{a}	80.0±8.1^{b}	66.6±10.4^{c}

*N: Newton; SD: standard deviation.
Variables are presented as mean (± standard deviation), as they followed a normal distribution. Significantly different groups are indicated using different letters as superscripts ($p < 0.05$). Groups 1, 2, and 3 refer to the modified Becker suture, modified Krackow suture, and modified double-Tsuge suture, respectively.

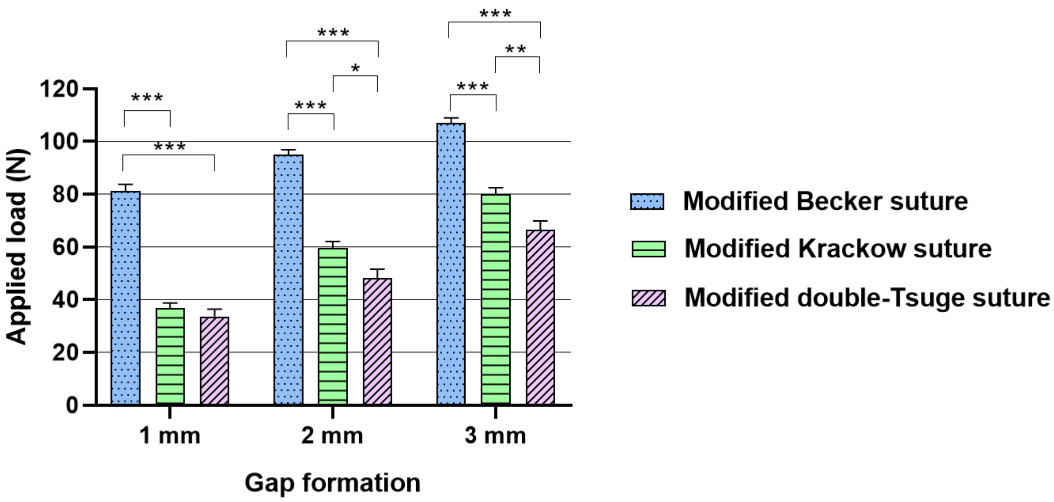

Figure 4 Load to 1 mm gap formation, 2 mm gap formation, and 3 mm gap formation for each group. Asterisks denote significant differences among the groups. (n = 10; *, **, and *** indicate P < 0.05, P < 0.01, and P < 0.001, respectively; error bars indicate the standard error of the mean).

Maximum Failure Load: The Shapiro–Wilk test showed normality for all three groups. The mean maximum failure load values were 133.0 ± 8.5 N in group 1 (modified Becker suture), 128.1 ± 11.8 N in group 2 (modified Krackow suture), and 88.3 ± 10.9 N in group 3 (modified double-Tsuge suture) (Table. 2).

The maximum failure load showed a statistically significant difference (One-way analysis of variance, $p < 0.05$) among the three suture types. The results of the post hoc Tukey test indicated that the maximum failure load was significantly higher in groups 1 and 2 than in group 3 ($p < 0.001$); however, there was no significant difference between groups 1 and 2 (Fig. 5).

Modes of failure: After the biomechanical test, we monitored and recorded any instances of failure. The modified Becker suture group (n = 10) and modified Krackow suture (n = 10) failed due to suture breakage (n = 10). The modified double-Tsuge suture group (n = 10) failed because of suture breakage (n = 4) or pull-out (n = 6) (Table. 3).

Table 2 Maximum failure load.

Maximum failure load (Mean ± SD)		
Group 1	**Group 2**	**Group 3**
133.0±8.5[a]	128.1±11.8[a]	88.3±10.9[b]

*N: Newton; SD: standard deviation.
Variables are expressed as mean ± SD, as they followed a normal distribution. Statistically significant groups are indicated using different superscript letters (p <0.05). Groups 1, 2, and 3 refer to the modified Becker suture, modified Krackow suture, and modified double-Tsuge suture, respectively.

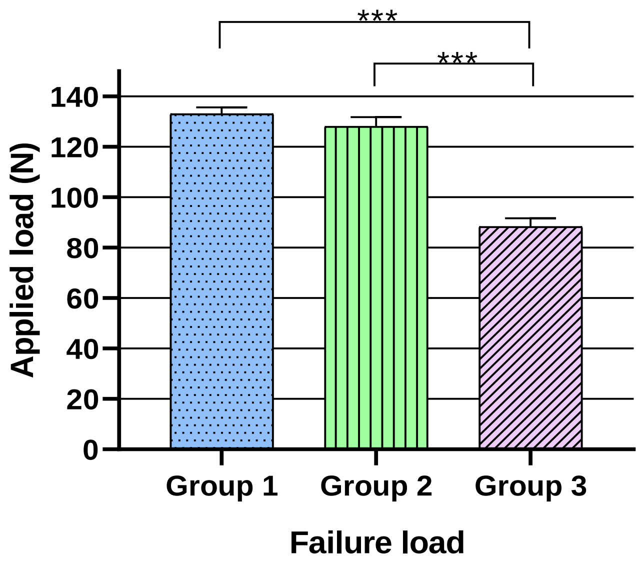

Figure 5 Load to failure for each group.
Asterisks indicate that there are statistically significant differences among the groups. (n = 10; *** indicates P < 0.001. Error bars indicate the standard error of mean). Groups 1, 2, and 3 refer to the modified Becker suture, modified Krackow suture, and modified double-Tsuge suture, respectively.

Table 3 Types of failure.

Group	Failure types
Group 1	Suture breakage (n = 10)
Group 2	Suture breakage (n = 10)
Group 3	Suture breakage (n = 4) Suture pull-out (n = 6)

Groups 1, 2, and 3 refer to the modified Becker suture, modified Krackow suture, and modified double-Tsuge suture, respectively.

Discussion

Compared with bone anchors, which have high cost and relatively high morbidity, such as infection, foreign body reaction, and pull-out from the bone, transosseous sutures (TOS) are frequently used in humans and can withstand similar tension while having relatively few side effects (Barros *et al*., 2010; Cho *et al*., 2012; Christen *et al*., 2022). Consequently, several TOS have been studied in clinical medicine. In veterinary medicine, the TOS technique has also been studied for repair of the distal common calcaneal tendon.

After repairing common calcaneal tendon, there is no difference in the maximum tendon strain between fixing and not fixing the tarsal joint, and muscle contraction continues during weight bearing (Lister *et al*., 2009) Therefore, when common calcaneal tendon rupture occurs, a TOS method that can withstand strong tension is necessary.

Early protected mobilization is crucial during the tendon repair process. To achieve this, a suture technique that provides stiff and sturdy repair throughout the initial healing phase is of primary importance (Boyer MI *et al*., 2001; Gelberman *et al*., 1986). This study considers six aspects of the suture technique for achieving initial tendon strength. The first aspect is the suturing method. The three suture techniques selected in this study have demonstrated appropriate methods for flat tendon repair with sufficient strength and promising outcomes in various studies (Labana *et al*., 2001; Angeles *et al*., 2002; Jordan *et al*., 2015; Wilson *et al*., 2014). The second is the tension applied to the sutures. By applying a consistent baseline tension to the suture, the tension on the strands of the repair is balanced, thereby preventing gaps from forming during the initial stages of the active motion of the tendon. When 10% shortening of the tendon segment is applied, the slight tension in the core suture significantly enhances the ability of the surgical repair to resist gaps (Wu and Tang, 2014). Therefore, in this study, a 10% tension was applied to the suture. The third aspect is the purchase distance of the core suture. For optimal tendon repair, the ideal suture purchase is around 7–10 mm. If the suture purchase was < 4 mm, the repair would significantly weaken. However, increasing the suture purchase from 10 mm to 12 mm does not result in a significant increase in strength (Tang *et al*., 2005). Therefore, in this study, the suture purchase was set at 7 mm, and the crisscrossing pattern suture spacing was set at 3.5 mm for both group 1 (modified Becker suture) and group 2 (modified Krackow suture). The fourth aspect is the suture material. In the locked, 4-strand cruciate repair technique, Fiber wire provided a greater tensile strength than Ethibond and Nylon. Additionally, it exhibited the lowest peak-to-peak displacement and elongation and the highest stiffness among them (Bisson *et al*., 2008; Miller *et al*., 2007). Therefore, a fiber wire was chosen as the suture material to minimize gap formation during tendon repair. The fifth aspect is the number of strands used in the suture. Numerous in vitro studies have confirmed the widely accepted fact that, with the increase in number of suture strands across the repair site, the ability to resist gap formation, failure strength, and fatigue strength during cyclic loading increases proportionally (Wu and Tang, 2014). The use of 4-strand repairs is considered appropriate because of their combination of enhanced tensile strength and gliding characteristics, as well as ease of execution (Wu and Tang, 2014). Therefore, in this study, four strands were chosen, considering the size that can be applied to the tendon. Finally, the knot was applied to the sutures. With the increase in number of knots, the ultimate tensile strength also increased, but it did not increase beyond six throws (Le *et al*., 2012). Therefore, in this study, six throws were applied to the knots using three different suturing techniques.

In this study, three suture techniques were compared considering the six aspects mentioned above. A modified Becker suture was used in the first group. The modified Becker suture demonstrated the strongest resistance in forming 1 mm, 2 mm, and 3 mm tendon gaps. This is because the modified Becker suture has a strong gap resistance due to its six cross-locks when tension is applied to the tendon. The six cross-locks serve as anchor points to increase the gap resistance, and it is likely that increasing the number of cross-locks would further strengthen the gap resistance. Collagen in the tendon core is oriented longitudinally, whereas that in the epitenon takes on an interlacing lattice form. As a result, when a longitudinal shearing force occurs, the epitenon grasps it and converts longitudinal loads into compression, which contributes to a strong gap resistance (Greenwald and Hong, 1994; Howard *et al*., 1997; Jordan *et al*., 2015; Woo *et al*., 2005). In the second group, the tendon was repaired using the modified Krackow suture technique. The Krackow suture consists of a continuous series of suture loops that firmly grip tendon bundles and prevent suture slippage (Ostrander *et al*., 2016; Wilson *et al*., 2014). Formed with 2 mm and 3 mm gaps, the modified Krackow suture demonstrated the second highest resistance among the three groups. In the third group, the tendon was repaired using the modified double-Tsuge technique. Formed with 1 mm, 2 mm, and 3 mm gaps, the modified double-Tsuge suture demonstrated the lowest resistance among the three groups. A modified double-Tsuge suture with a locking loop secured the tendon in place by compressing the collagen fibers of the tendon perpendicular to its axis. This technique minimizes the bulk at the laceration site, allowing for smooth vascular flow and enables flexion movement at the tendon site for early active motion (Lister *et al*., 2009). However, in this study, the resistance to tension was the lowest among the tested techniques.

During load-to-failure testing, all suture repair models in both groups 1 and 2 failed at the square knot. Several other studies have reported similar results. According to previous studies, when comparing the tension of sutures in tendons connected to bars, if the suture throw exceeds 5 times, suture breakage at the level of the knot is caused by frictional forces under the bar (Ostrander *et al*., 2016). In this study, a suture throw of six was used for comparison of the results with those of previous studies, and it is likely that the actual failure load exceeded the breaking strain of the suture. Consequently, it was considered impossible to compare the failure loads of groups 1 and 2. In group 3, suture breakage (n = 4) and suture pull-out (n = 6) were observed. Tsuge suture, provided a single loop to secure the tendon, resulting in a relatively weak gripping force and the loop becoming detached from the tendon. Consequently, the measured failure load was lower because the suture pull-out resistance was weaker than the suture breakage strength.

Two parallel 1.2 mm bone tunnels were drilled in the calcaneal bone to enable anatomical repair. The sutures were passed in a parallel manner to offset the forces generated by the non-parallel sutures. Sutures passing through the tendon stump entered the entrance of the tunnel created at the common calcaneal tendon insertion. This allowed for better tendon apposition. The three suture techniques used in this study showed good alignment on the parallel bone tunnels, as they were all in the same plane.

When the gap between tissues exceeds 3 mm, previous study has indicated that there is no increase in the ultimate strength or stiffness of the repair site during the initial healing phase (Gelberman *et al*., 1986). These findings imply that tendons with a gap larger than 3 mm may be at higher risk of rupture during the early phase of healing. Therefore, the load required to cause a 3 mm gap formation may be a more critical factor in clinical healing than the load required for failure.

According to a previous study, the force of the Achilles mechanism is 4.1 N/kg in dogs (Moores *et al*., 2004). Using the mean body weight of the samples in our experiment, we calculated that the average Achilles mechanism force is 41.8 N. In our study, we found that the modified Becker suture was able to withstand the formation of a 1 mm gap in the Achilles mechanism force, while the modified Krackow suture and modified double-Tsuge suture were able to withstand the formation of a 2 mm gap. Our findings indicate that, in a static standing position, the repaired Achilles tendon using the suturing methods used in this study may be able to withstand in vivo forces without significant formation of gaps. However, it is unlikely that the repair could sustain cyclic or repetitive forces related to movements, such as walking or rising from a sitting position.

This study has some limitations. First, when interpreting the findings of this study, it should be considered that applying the suturing technique to a pathologic common calcaneal tendon may yield different results. When avulsion occurs due to a pathological condition of the tendon, such as inflammation or soft tissue swelling, the suture holding capacity may be compromised compared to that of a normal tendon. Second, the methods used may not accurately reflect the actual movement of the hock joint. The study did not include repetitive cyclic loading or flexion movement tests on the repaired site. If further study compares cyclic loads in vitro, it may be possible to reflect the actual movement of the hock joint. Additionally, applying the three suturing techniques to actual clinical patients would allow for a comparison of suturing methods in pathological tendon conditions.

According to the experimental results of this study, the modified Becker suture method is biomechanically superior to other suture methods. Although all three suturing techniques were able to withstand the force applied to the Achilles tendon during the formation of 2 mm and 3 mm gaps, only the modified Becker suture could withstand the Achilles mechanism force and exhibited the highest tension when a 1 mm gap was formed. Therefore, in the case of a distal common calcaneal tendon avulsion rupture, a modified Becker suture can be considered a potential treatment option. Furthermore, with further additional experimentation, it could potentially become the golden standard for such cases.

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