Radial Meniscal Tears Are Best Repaired by a Modified "Cross" Tie-Grip Suture Based on a Biomechanical Comparison of 4 Repair Techniques in a Porcine Model

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Background: The tie-grip suture can fix radial tears more rigidly than simple conventional sutures. However, one shortcoming is the residual gap at the central margin of the tear. The tie-grip suture was modified to address this issue and named the "cross tie-grip suture."

Purpose/Hypothesis: The purpose of this study was to compare the suture stability and strength among 4 suturing techniques: the original tie-grip, cross tie-grip, and 2 conventional sutures (double horizontal and cross). It was hypothesized that the cross tie-grip suture would show the least displacement and resist the greatest maximum load.

Study Design: Controlled laboratory study.

Methods: A total of 40 fresh-frozen porcine knees were dissected to acquire 80 menisci; 20 menisci were tested in each suture group. A radial tear was created at the middle third of the meniscal body. Repair was performed with the following: original tie-grip, cross tie-grip, double horizontal, and cross sutures. The mechanical strength of sutured menisci was evaluated using a tensile testing machine. All menisci underwent submaximal loading and load to failure. The gap distance and ultimate failure load were compared using analysis of variance. The failure mode was recorded after load-to-failure testing.

Results: Displacement after 500 cycles was significantly smaller in the cross tie-grip group (0.4 $\pm$ 0.3 mm) compared with the tie-grip (0.9 $\pm$ 0.6 mm), double horizontal (1.2 $\pm$ 0.7 mm), and cross suture groups (1.4 $\pm$ 0.6 mm) ($P < .05$). The ultimate failure load was significantly greater in the cross tie-grip (154.9 $\pm$ 29.0 N) and tie-grip (145.2 $\pm$ 39.1 N) groups compared with the double horizontal (81.2 $\pm$ 19.9 N) and cross suture groups (87.3 $\pm$ 17.7 N) ($P < .05$). Tissue failure was the most common mode of failure in all groups.

Conclusion: Upon repair of radial meniscal tears, the cross tie-grip suture showed less displacement compared with that of the tie-grip, double horizontal, and cross sutures and demonstrated equivalent load to failure to that of the tie-grip suture at time zero.

Clinical Relevance: The cross tie-grip suture provided high resistance to displacement after repair of radial tears and may be advantageous in healing for radial meniscal tears.

Keywords: radial meniscal tears; meniscal suture technique; cyclic load testing; rip-stop sutures

Repair of meniscal tears whenever possible is preferable to resection to maintain the role of the meniscus, such as knee joint stability, load distribution, proprioception, and prevention of osteoarthritis.[1,15,22] Among the different types of meniscal tears, radial tears are challenging to repair because hoop stress caused by weightbearing leads to distraction force at the tear site.[2] In addition, sutures that are perpendicular to the radial tear are parallel to the collagen fibers, which are mainly aligned circumferentially, resulting in cutout of the sutures.[3,7,18,23] However, for tissue healing and restoration of function, stable fixation with minimal gapping is ideal.[10,11] Despite the difficulty in repair, radial meniscal tears are important to address because they are not uncommon.[12,16] Furthermore, complete radial tears are equivalent to meniscectomy,[19] but even partial preservation of the meniscus can maintain some load transmission and distribution across the joint.[6] Therefore, the meniscus should be restored whenever possible. However, clinical success by current repair methods for radial tears is still limited,[20,25] and thus, a suture

The Orthopaedic Journal of Sports Medicine, 8(7), 2325967120935810
DOI: 10.1177/2325967120935810

configuration that can approximate and stabilize the tear is sought.

A variety of suture methods have been introduced to repair radial meniscal tears. Horizontal sutures and cross sutures[18] are simple, but as mentioned earlier, the sutures that bridge the gap are almost parallel to the fibers, and thus, tissue failure or slippage is a common limitation. Nakata et al[21] introduced the "tie-grip suture," which involves inside-out repair tied over the capsule consisting of 2 vertical mattress sutures and 2 horizontal sutures passed over the vertical mattress sutures. This method provides stable fixation because the vertical mattress sutures bundle the circumferential fibers and act as rip stops for the horizontal sutures. However, 2 vertical mattress sutures pull apart the central margins of the radial tear, making a gap at the inner rim of the sutured site, which is unfavorable for healing. A further modification of the tie-grip suture by crossing the mattress sutures, named the "cross tie-grip suture," would potentially address this problem.

The purpose of this study was to provide biomechanical testing results for the original tie-grip suture and cross tie-grip suture. In addition, conventional sutures, namely the double horizontal and cross sutures, were tested for comparison. The hypothesis was that the cross tie-grip suture would show less gap formation and resist a greater maximum load compared with that of the original method and the conventional double horizontal and cross sutures. This report compared the abovementioned 4 suture methods for radial meniscal tears in a controlled setting.

METHODS

A total of 40 fresh-frozen porcine knees, aged 6 months, were obtained from a local abattoir, and 80 menisci were resected from the knees. The use of porcine knees, which were originally processed for food consumption, did not require approval from the institutional review board. The frozen knees were thawed at room temperature and tested immediately after thawing. The menisci were resected at the meniscocapsular junction. All menisci were visually inspected to ensure that there was no damage to meniscal tissue. There were 20 menisci (10 medial, 10 lateral) randomly chosen for each group: original tie-grip suture, cross tie-grip suture, double horizontal suture, and cross suture. The resected menisci were kept in saline solution until mounting on the load testing machine and sprayed with saline solution throughout the testing process. Tensile testing of meniscal repair tissue was performed using established instrumentation and protocols.[26] A No. 11 scalpel was used to create a radial tear extending from the central margin to 2 mm from the meniscocapsular junction at the middle third of the meniscal body, equidistant from the anterior and posterior horns.[5] Suture configurations were tested in random order.

Suture Techniques

All radial tears were repaired with the same nonabsorbable suture material (Meniscus Suture 2-0 Polyester Hollow; Stryker Japan) and by a single experienced orthopaedic surgeon (D.A.). The cross tie-grip and original tie-grip suture techniques were performed as shown in Figure 1. Both configurations are inside-out repair. The difference between the 2 configurations was that with the cross tie-grip suture, the vertical mattress suture was passed diagonally, crossing the tear, whereas with the original tie-grip suture, it was passed parallel to the radial tear. Double horizontal and cross suture techniques were performed according to a previous report by Matsubara et al[18] (Figure 1). Similar to the technique by Nakata et al,[21] our method was performed as an inside-out technique with knots tied over the capsule. There were 4 total knots tied, each with a square knot with an additional simple knot.

Biomechanical Testing

The sutured menisci were set in a tensile testing machine[26] with custom clamps. The tensile testing machine consisted of an electric actuator (PWA II Cylinder; Oriental Motor), which moved the cylinder and pulled the meniscus while the load cell (LCTA-A-1KN; Kyowa Electronic Instruments) measured the tensile force generated during surgery. The load cell signal was transferred to a personal computer via the load cell amplifier (TUSB-S01LC2Z; Turtle Industry). The resolution of the electric actuator was 0.01 mm, and the load cell was set at 1.0×10^{-7} N. A metric ruler with 1-mm increments was positioned parallel to the clamp to serve as a calibration scale for image processing as described later (Figure 2). Biomechanical testing was performed in reference to previous reports. The preloading protocol was based on the study by Lee et al,[14] and performed at 5 to 20 N, but it was modified to 300 cycles at 0.5 Hz. Submaximal loading was replicated from a protocol by Beamer et al.[5] Subsequently, a digital photograph (OM-D E-M5 Mark II; Olympus) was taken with the menisci under a 5-N load,[5] identified as a gap distance at cycle 0. Next, submaximal loading was performed for 500 cycles from 5 to 20 N at 1 Hz. The cycle was paused at 100, 250,

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Accepted for presentation at the annual meeting of the AOSSM, July 2020.

Final revision submitted December 21, 2019; accepted December 23, 2019.

The authors have declared that there are no conflicts of interest in the authorship and publication of this contribution. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was waived by Kobe University Graduate School of Medicine.

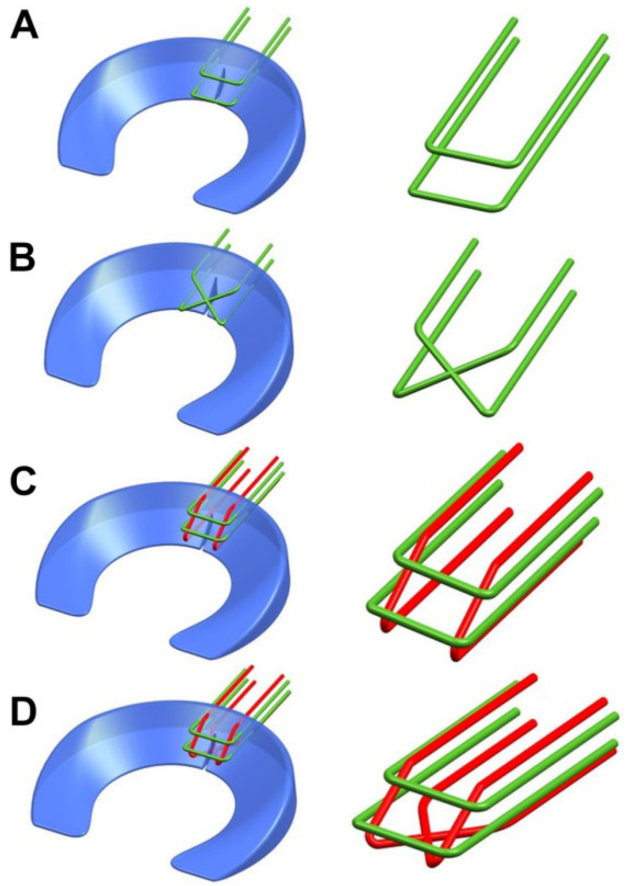

Figure 1. Schematic representations. (A) The double horizontal suture. (B) The cross suture. (C) The tie-grip suture: vertical mattress sutures are followed by 2 horizontal sutures. (D) The cross tie-grip suture: vertical mattress sutures are crossed diagonally, followed by 2 horizontal sutures.

and 500 cycles for digital photographs to be taken. The gap distance was measured similarly to the method reported by Lee et al.[14] Specifically, the digital photographs were uploaded using image processing software (ImageJ; United States National Institutes of Health), which could be used as an electronic ruler. Using this software, 10 mm was measured as pixels on the metric ruler to serve as a standard scale (measurement 1). The resolution using ImageJ was 0.04 mm/pixel. Then, the gap distance between the lesion edges was measured (measurement 2) in pixels. The gap distance was determined by dividing measurement 2 by measurement 1 and then multiplying the value by 10 mm.[14] Finally, load-to-failure testing was conducted at 5 mm/min, consistent with previous reports.[4,9,17,18] The failure mode (tissue failure, suture failure, or knot failure) was recorded. The gap distance was defined as the width of the gap at a given cycle, whereas displacement was the difference in the gap distance at a given cycle compared to the gap at cycle 0: gap distance at a given cycle (mm) – gap distance at cycle 0 (mm).

Statistical Analysis

Primary parameters tested were gap distance after cyclic loading among the 4 suture techniques. One-way analysis of variance and the Tukey-Kramer post hoc test were used to analyze any difference between groups, with the level of significance set at $P < .05$.

The reproducibility of gap distance measurements was assessed by calculating the intraclass correlation coefficient from measurements collected during pilot testing. The intraclass correlation coefficient was 0.90, and the standard error of measurement was 0.10 mm. Also, based on pilot testing data, an a priori sample size calculation to detect a difference of 0.1 mm suggested that 18 specimens per group would be needed to have statistical power of 80% ($\beta = .20$) at an alpha level of .05.

RESULTS

Gap Distance and Displacement

A significant difference was observed for gap distance among the 4 groups upon submaximal loading after 100, 250, and 500 cycles ($P < .01$). The gap distance was significantly smaller after 100, 250, and 500 submaximal cycles in the cross tie-grip and tie-grip suture groups compared with conventional suture groups ($P < .05$) (Table 1). Displacement after 500 submaximal cycles of loading was significantly less in the cross tie-grip suture group compared with the tie-grip suture group ($P < .05$) (Figure 3).

Ultimate Failure Load

A significant difference was seen within the 4 groups for ultimate failure load ($P < .01$). Within the groups, both the tie-grip and cross tie-grip suture groups showed a greater ultimate failure load compared with that of the double horizontal and cross suture groups ($P < .05$) (Figure 4). There was no significant difference in ultimate failure load between the tie-grip and cross tie-grip suture groups ($P = .29$) (Table 1).

Failure Mode

In all groups, besides 1 knot failure in the tie-grip suture group, the mode of failure was tissue failure. Tissue failure was caused by the suture cutting through meniscal tissue.

DISCUSSION

This study provides biomechanical testing results for the original tie-grip suture and the newly introduced cross tie-grip suture, and comparisons were made to the conventional double horizontal suture and cross suture for repair of radial meniscal tears. The most important finding of the current study was that the cross tie-grip suture showed less displacement after 500 submaximal loading cycles, indicating greater resistance to gapping after repetitive distraction force to the repaired menisci compared with that of the

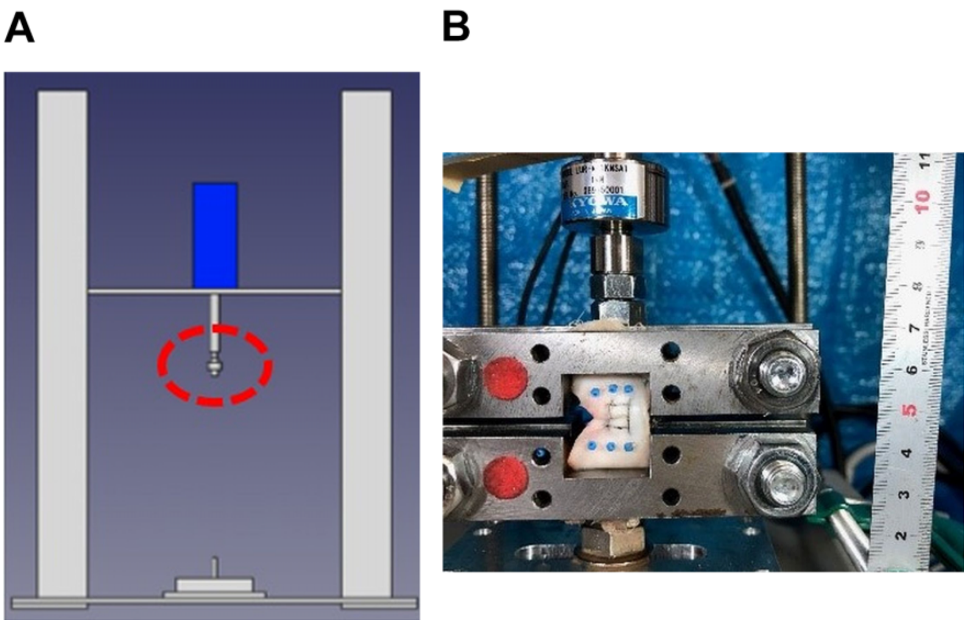

Figure 2. (A) The schematic diagram shows the biomechanical testing setup without the clamps. The location of the load cell is indicated by the red dotted circle. (B) The picture shows a sample meniscus secured between 2 custom clamps. The metric ruler was placed in the same plane as the meniscus for standardization of measurements.

TABLE 1
Ultimate and Submaximal Loading Data[a]

	Original Tie Grip	Cross Tie Grip	Double Horizontal	Cross
Ultimate failure load, N	145.2 ± 39.1	154.9 ± 29.0	81.2 ± 19.9	87.3 ± 17.7
Gapping after cyclic load, mm				
0 cycles	1.2 ± 0.7	0.7 ± 0.5	1.7 ± 1.0	2.4 ± 1.2
100 cycles	1.6 ± 0.8	1.1 ± 0.7	2.2 ± 1.1	2.8 ± 1.4
250 cycles	1.8 ± 0.8	1.2 ± 0.7	2.5 ± 1.2	3.4 ± 1.5
500 cycles	2.1 ± 0.8	1.3 ± 0.7	2.9 ± 1.6	3.8 ± 1.6
Displacement after 500 cycles, mm	0.9 ± 0.6	0.4 ± 0.3	1.2 ± 0.7	1.4 ± 0.6

[a]Data are shown as mean ± SD.

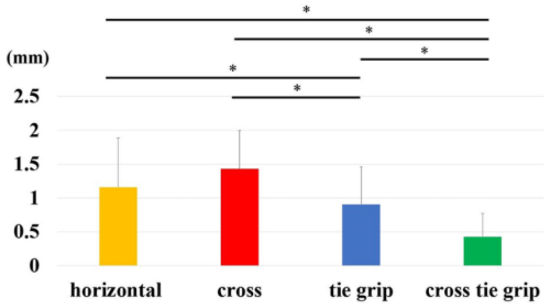

Figure 3. Displacement after 500 cycles. *$P < .05$.

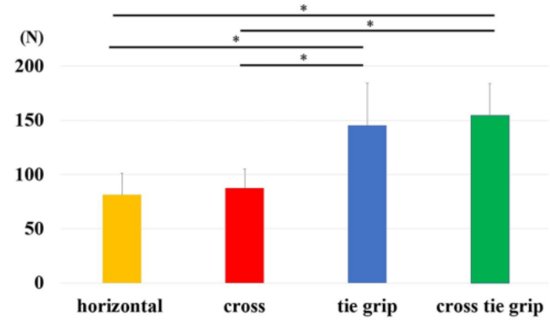

Figure 4. Ultimate failure load. *$P < .05$.

tie-grip suture and conventional suture methods at time zero, which supported the hypothesis.

Current suture methods for radial meniscal tears have produced limited clinical outcomes.[20] A systematic review by Moulton et al[20] reported improvement in patient outcomes; however, the results were only for the short term to midterm. Tsujii et al[25] reported on the 2-year clinical outcomes of repairs of radial tears in the posterior lateral meniscus combined with the anterior cruciate ligament reconstruction. Upon second-look arthroscopic surgery, 90% (27/30) of the patients had complete or partial meniscal healing. Despite the high healing rate, chondral lesions in the lateral tibial plateau progressed during the 2-year follow-up.[25] Therefore, a suture configuration to approximate and stabilize the radial tear is still needed. Currently, the tie-grip suture is an anatomically and biomechanically valid method that provides stable fixation for radial meniscal tears.[21] However, the tendency for the avascular zone, or the "white-white zone," to form a gap can negatively affect healing.[24] To address this point, a modification by crossing the sutures was made to improve the tie-grip suture, and it was named the "cross tie-grip suture." The current study results demonstrated the ability for the cross tie-grip suture to resist gapping better than could previous methods at time zero.

The strength of this study is that not only did it introduce a new cross tie-grip suture and compare it with the original method, but it also tested the commonly used cross and double horizontal sutures, making it possible for surgeons to make a direct comparison among the suture methods. Although there are previous studies[8,17,18] reporting biomechanical testing data for the tie-grip suture, cross suture, and double horizonal suture, direct comparisons could not be made because laboratory conditions differ depending on the report. Comparisons were made with the hope of being a source of evidence to provide biomechanical information for surgeons when repairing radial meniscal tears.

The main advantage of the cross tie-grip suture is resistance to gapping compared to that of past suture methods. The cross suture reported by Matsubara et al[18] showed significantly less gapping after 500 submaximal cycles compared to the double horizontal suture. Recent reports[8,23] have used sutures equivalent to rip stops, such as rebar repair, a hybrid technique (tie-grip suture), hashtag, cross tag, and a combined hybrid tunnel technique, which have greatly improved the ability to resist gapping. Although direct comparisons cannot be made among the different reports, gapping after 500 submaximal cycles for the tie-grip suture in our biomechanical test is similar to the result reported by Buckley et al.[8] Furthermore, additional improvement in gap closure was achieved using the cross tie-grip suture. The cross tie-grip suture provided stability with the use of 2 vertical sutures as rip stops and minimal gapping by crossing the vertical sutures, ensuring closure of the gap.

The maximum loads for the tie-grip and cross tie-grip sutures in this study were congruent with the result for rebar repair recently published by Massey et al[17] in which the maximum load was 124.1 ± 27.1 N. In short, rebar repair is an inside-out technique with 2 horizontal sutures placed next to 2 vertical sutures that act as rip stops, which resemble the tie-grip suture.[17] Massey et al[17] also tested the double horizontal and cross sutures with maximum loads, resulting in 85.5 ± 22.0 N and 76.2 ± 28.8 N, respectively, which were also similar to findings in the current study. Buckley et al[8] performed biomechanical testing comparing the tie-grip suture to a 2-tunnel transtibial technique (horizontal mattress suture augmented with a 2-tunnel transtibial technique) and a combined hybrid tunnel technique (transtibial technique with vertical mattress sutures).[8,13] The average maximum loads for the 3 sutures were all >250 N without any statistically significant difference. The average maximum load for the tie-grip suture was higher than that in any previous reports regarding suture methods for radial meniscal tears. Therefore, the cross tie-grip suture, which was comparable to the tie-grip suture in the current study, holds potential as a treatment modality based on in vitro biomechanical testing.

This study is not without limitations. First, the use of porcine menisci does not allow for a direct comparison of the absolute values of displacement and ultimate failure load to those of human menisci. However, the use of porcine menisci for biomechanical testing of suture methods is common in previous literature.[4,5,14] Moreover, using porcine menisci even for a relative comparison between suture methods can be advantageous because the menisci were obtained from 6-month-old pigs from a common environment; however, in humans, their backgrounds vary, and specimens are often from older patients, who may not have visual damage but can be assumed to have tissue degeneration.[7,8,18,23] Second, this experimental study only applied distraction force mainly because of the testing device. However, this is a common limitation for all biomechanical tests on menisci because of the difficulty in reproducing the complex combination of distraction, shear, and compression forces in the in vivo knee. However, as Matsubara et al[18] described, the force applied perpendicular to the tear and parallel to the horizontal sutures creates a "worst-case scenario" condition. Therefore, it can be said that these sutures are tested in severe conditions, and by applying the same force for each suture method, direct comparisons can be made. Third, repair of the meniscus in the clinical setting is usually performed arthroscopically, obviously in an intact joint capsule. In this study, repair was performed under direct observation for accurate suturing. Arthroscopic suturing could cause slight differences in tension and location of the suture and affect the absolute value of displacement and ultimate failure load. In reference to the technical feasibility of the cross tie-grip suture in a clinical setting, the technique can be performed arthroscopically in the middle or midposterior zone of the meniscus. It is difficult to suture radial tears in the other zones. However, most radial tears occur in the midbody of the meniscus,[16] and thus, this technique can be applied to many cases involving radial tears. Obliquity across the radial tear can be achieved by bending the needle before insertion into the knee joint. Finally, with this being a biomechanical study using cadaveric specimens, the effect of healing was not considered. Further clinical studies are necessary to determine the effect on meniscal healing with the use of the cross tie-grip suture.

CONCLUSION

Upon repair of radial meniscal tears, the cross tie-grip suture showed less displacement compared with that of the original tie-grip, double horizontal, and cross sutures and demonstrated an equivalent load to failure to that of the original tie-grip suture. The simple modification of crossing the vertical mattress sutures increased the ability of the suture to resist gapping at time zero. This suture method can become a viable option for surgeons when repairing radial meniscal tears.

ACKNOWLEDGMENT

The authors thank Stryker Japan K.K. for providing the porcine knees, suture materials, and devices.

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