Analysis of a New All-Inside Versus Inside-Out Technique for Repairing Radial Meniscal Tears

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Purpose: The purpose of this study was to compare gap formation, strength, and stiffness of repaired radial tears of the meniscus treated using a new all-inside technique versus a traditional inside-out suture technique. **Methods:** Radial tears were created in 36 fresh-frozen porcine menisci. Repairs were performed using a novel all-inside suture-based meniscal repair device or an inside-out technique. The repairs were tested for cyclic loading and load to failure. The displacement, response to cyclic loading (100, 300, and 500 cycles), and mode of failure were recorded, and the construct's stiffness was calculated. **Results:** The all-inside repairs using the novel device resulted in a significantly lower displacement (gap formation) after 100, 300, and 500 cycles ($P = .002$, $P = .001$, and $P = .001$, respectively). The ultimate load to failure was significantly greater for the all-inside repairs (111.61 N *v* 95.01 N; $P = .03$). The all-inside repairs showed greater stiffness (14.53 N/mm *v* 11.19 N/mm; $P = .02$). The all-inside repairs failed most often by suture breakage (suture failure). The inside-out repairs failed most commonly when the suture pulled through the tissue (tissue failure) ($P < .001$). **Conclusions:** For repair of radial tears of the meniscus, the vertical suture configuration created by the all-inside technique resulted in lower displacement, higher load to failure, and greater stiffness compared with the horizontal inside-out technique. **Clinical Relevance:** In a porcine specimen meniscus repair model, the biomechanical properties of a vertical all-inside technique were superior to that of a horizontal inside-out technique. Future studies of biomechanical and clinical outcomes in human meniscal repairs with this device are warranted to explore whether this repair method is valuable to clinical practice and patient outcomes.

Radial tears of the meniscus are a distinct pattern of injury that can render the meniscus incompetent.[1] When the peripheral circumferentially oriented fibers of the meniscus are disrupted, the tissue's ability to resist hoop stresses is lost, leading to increased contact pressures and an early onset of arthrosis.[2-4]

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All-inside devices have been developed to pass sutures arthroscopically in an effort to treat meniscal tears without anchoring devices or a separate incision. Previous investigations by our group have shown that all-inside devices have compared poorly to an inside-out technique for longitudinal tears of the meniscus.[5] We believe this is because of the orientation of the suture with all-inside devices that are available at present. Current all-inside devices used for repair of radial tears place the suture horizontally in a fashion similar to that of an inside-out repair but without fully encircling the tear at the periphery.[5] In attempts to create a biomechanically superior repair, a novel device has been developed that uses an articulated jaw to grasp the meniscus and pass a suture vertically from the undersurface of the meniscus. As a result, when applied to a radial tear, the suture is perpendicular to the tear and effectively encircles the radially oriented collagen fibrils at the site of the tear, binding them together.[4] This, in theory, would make for a more robust repair with less suture pull-through within the meniscus.

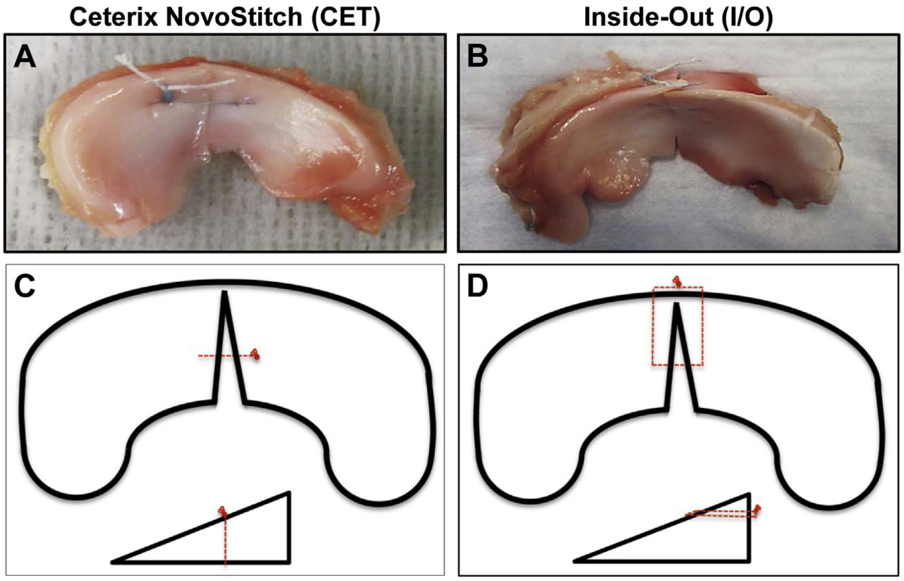

Fig 1. Meniscal repairs with (A) the Ceterix NovoStitch meniscal repair technique and (B) the 2-0 Force Fiber inside-out suture technique, and (C) surgical repairs using the Ceterix NovoStitch Disposable Suture Passer and (D) the 2-0 Force Fiber inside-out suture technique. Red dotted lines depict the suture lines for the repair techniques.

The purpose of this study was to compare gap formation, strength, and stiffness of repaired radial meniscus tears treated using a new all-inside technique versus a traditional inside-out suture technique. We hypothesized that the response to cyclic loading and the load to failure of radial tears treated with this novel device would be superior to those of a traditional inside-out repair.

Methods

Preparation and Repair

Paired (medial and lateral) fresh-frozen porcine menisci were randomly assigned to 2 groups: NovoStitch (Ceterix Orthopaedics, Menlo Park, CA) (n = 18) or inside-out repair (n = 18). Nine medial and 9 lateral menisci were used in each group and were loaded in the same fashion. All menisci were harvested intact by resecting the surrounding tissue at the meniscocapsular junction and were thawed 8 hours before testing. A No. 11 surgical blade was used to create a radial tear within the middle third of the meniscal body equidistant from the anterior and posterior horns. The tears extended from the central margin to 2 mm from the meniscocapsular junction.

The all-inside repair device was used to pass a suture vertically through the meniscus from bottom to top, 5 mm on either side of the tear and 4 mm from the peripheral meniscal rim in accordance with the manufacturer's instructions (Fig 1 A and C) Two sliding half-hitches were tied, followed by 5 alternating half-hitches, to create 3 square knots. A traditional inside-out meniscal repair technique was used to complete the inside-out suture repair.[6,7] One strand of No. 2-0 Force Fiber (Teleflex Medical, Research Triangle Park, NC) was passed 5 mm from the tear on either side and 4 mm from the peripheral meniscal rim using a straight Keith needle. Similarly, 3 square knots were tied using 7 throws (Fig 1 B and D) Once tied, the radial tear was completed by extending the incision through the peripheral rim of the meniscus, allowing for direct testing of the repair interface without influence from the intact meniscal rim. In both groups, the repairs were performed with 2-0 Force Fiber ultrahigh-molecular-weight polyethylene suture (Teleflex Medical, Research Triangle Park, NC). The suture was inspected for any damage incurred during the repair process, and specimens with evidence of suture compromise were discarded and replaced. Tissue moisture was maintained throughout testing using physiological 0.9% saline.

Biomechanical Testing

The repaired menisci were placed in custom-made aluminum clamps with a textured surface that tightened down with through bolts and grasped the meniscus, which was aligned perpendicular to the tear, and were mounted in a mechanical testing system (Instron 8511, Instron, Norwood, MA) (Fig 2). After 2 N preload, cyclic loading was performed between 5 and 20 N at a frequency of 1 Hz.[5,8,9] These loads were chosen based on the methods of numerous other studies that evaluated the biomechanical strength of meniscal repairs, because these loads are thought to approximate in vivo loads the meniscus faces.[10-12] Furthermore, these loads are in keeping with previous studies on meniscal repair by our group and others.[5,13-15] Data were recorded continuously (WaveMatrix; Instron, Norwood, MA). On each specimen, 3 sets of paired markings were placed on either side of the repair using India ink (Fig 2, red and green arrows). Gap formation

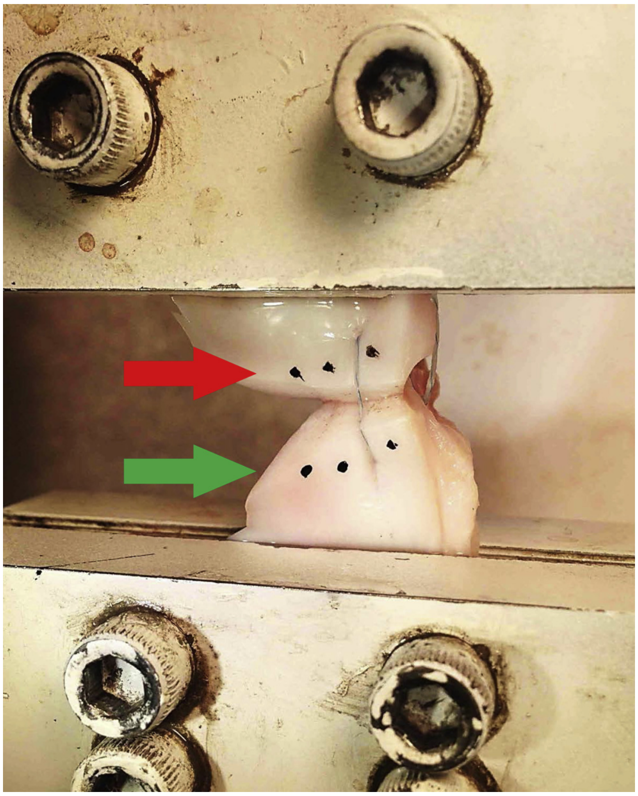

Fig 2. A representative specimen mounted in testing jig with India ink markings (arrows) visible on the specimen above and below the repair site.

(displacement) was recorded by measuring the distance between the center of paired markings on either side of the tear at a load of 5 N after cycles 0, 1, 100, 300, and 500 using a calibrated, high-resolution digital camera (PixeLINK PL-B681C; PixeLINK, Ottawa, Ontario, Canada). Displacement measurements were calculated as the vertical component of the measured distance, accurate to 1/100th of a millimeter (MATLAB, MathWorks, Natick, MA). Cycle 0 served as the reference value for reporting the displacements for subsequent cycles 1, 100, 300, and 500.

Load-to-failure testing was then performed at a rate of 3.15 $mm \cdot s^{-1}$. Stiffness was calculated as the slope of the load-displacement curve between 20% and 60% of the yield load. The mode of failure was recorded for each specimen: suture breakage (suture failure), suture pull-through (tissue failure), or a knot slip (knot failure).

Statistical Analysis

An a priori sample size calculation analysis was performed in accordance with an earlier investigation.[16] Eighteen specimens per group were adequate to detect a 20% change in the load to failure at 80% power (nQuery Advisor, version 7.0; Statistical Solutions, Boston, MA). The distribution of data was assessed for skewedness using the Shapiro-Wilk test. A paired Student *t* test was used to compare the load to failure and stiffness. A repeated measures 2-way analysis of variance with mixed modeling was used to compare the response to cyclic loading (cycles 1, 100, 300, and 500) between the 2 groups (inside-out and NovoStitch), with loading cycle and group as independent variables and gap formation as a dependent variable. The Fisher-Freeman-Halton exact test for contingency tables larger than 2×2 was used to assess differences in failure mode[17] (suture failure, tissue failure, knot slip) between groups (inside-out and NovoStitch) (IBM SPSS Statistics, version 21.0; SPSS, Chicago, IL). All comparisons were 2-tailed and $P < .05$ was considered significant.

Results

The data (failure load, stiffness, and displacement) were distributed normally ($P > .05$ for all cases). The all-inside and inside-out repairs showed no difference in initial gap formation (displacement) ($P = .19$). However, after 100, 300, and 500 cycles, the all-inside group had less gap formation (displacement) ($P =$ .002, .001, and .001, respectively) (Fig 3).

The all-inside group showed a higher load to failure and greater stiffness than the inside-out suture repair group ($P = .03$ and $P = .02$, respectively) (Fig 4, Table 1).

The mode of failure was different ($P < .0001$) between the groups. The inside-out repairs failed most often when the suture pulled through the tissue (tissue failure) (n = 14 [78%]). The suture failed 4 times (22%) and none of the knots slipped (0%). For the NovoStitch, the construct failed because of suture breakage (suture failure) most commonly (n = 13 [75%]). Tissue failure occurred 4 times (19%) and the knot slipped once (6%).

Discussion

The results of this investigation upheld the initial hypotheses. The all-inside repair had less displacement after cyclic loading, a higher load to failure, and greater stiffness than did the inside-out controls. Interestingly, the mode of failure also differed between the 2 groups. The all-inside repairs failed predominantly by suture breakage, and the inside-out group tended to pull through the tissue.

The architecture of the collagen fibrils within the meniscus create cleavage planes along which meniscal tears propagate.[4] Radial tears begin at the central margin where the collagen fibrils are organized predominantly in a radial fashion. They then propagate peripherally until they intersect with the circumferentially oriented fibers. When the tear progresses along a circumferential plane, it becomes a parrot beak tear. Current methods of meniscal repair rely on

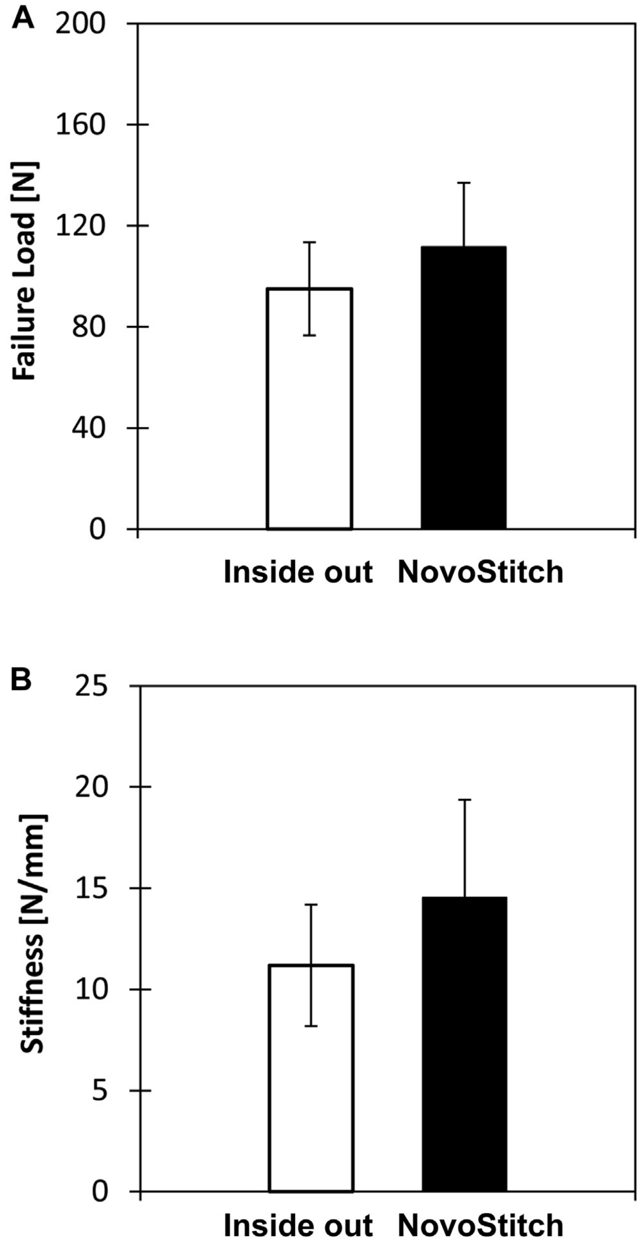

Fig 3. (A) Failure load and (B) stiffness depicted across the 2 repair groups.

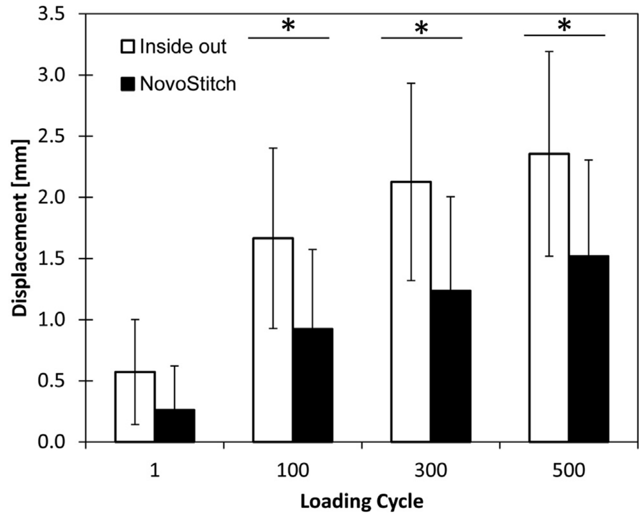

Fig 4. Displacement values after 1, 100, 300, and 500 cycles across the 2 repair groups. Asterisks denote statistical significance with respect to the other groups.

horizontal orientation of sutures that cannot bind the radially oriented fibers together (Fig 1 B and D). Because the new all-inside device passes a suture vertically through the meniscus, the suture repair is oriented perpendicular to the torn radial fibers, making the construct less likely to fail.[18] The resulting reactive force of the stitch is therefore directly opposite to the direction of displacement, whereas an inside-out repair stitch is oblique to it. We believe that the increased repair strength with a vertically oriented loop results from the fact that the loop is oriented perpendicular to the radial fibers, effectively encircling them and decreasing suture cleavage through the tissue.

Previous work has shown that a vertical loop of suture is significantly stronger than a horizontally oriented loop in the treatment of a longitudinal meniscal tear.[19] In this study, the vertical loop tended to fail by suture breakage, and the horizontal loop failed when it tore through the tissues. When considered in the context of this investigation, irrespective of the tear pattern, vertically oriented sutures appear to be better supported by the meniscal microarchitecture and therefore result in a stronger meniscal repair.

The gold standard for meniscal repair is an inside-out repair.[6] Because this method requires needle passage through the posterior capsule, neurovascular structures can be injured or tethered.[6,20] This factor has led to the development of all-inside meniscal repair devices. Current designs use nonabsorbable anchors deployed on the extra-articular side of the joint capsule, without making a separate incision. Although less invasive than inside-out techniques, the all-inside repair techniques are not without complications. In addition to neurovascular injury, irritation from the anchors and implant failure have been reported.[21]

The vascular supply to the meniscus is from the geniculate arteries, whose tributaries enter the meniscus peripherally. Arnoczky and Warren[22] described 3 distinct vascular zones of the meniscus, with the peripheral third having the greatest blood supply and the central third being nearly avascular in adults. Because radial tears begin in the central avascular zone of the meniscus, these injuries are often treated with local debridement of the unstable flaps. Because only 20% of the meniscus can be debrided without increasing tibiofemoral contact forces, and because recent studies suggest that central tears may heal, repair of radial tears may warrant consideration.[7,23]

Table 1. Load, Stiffness and Displacement Results for the 2 Repair Techniques

Technique	Load to Failure, N	Stiffness, N/mm	Cycles of Displacement, mm			
			1	100	300	500
Inside-out, SD	95.01	11.19	0.57	1.67	2.13	2.36
	18.44	3.00	0.43	0.74	0.81	0.84
NovoStitch, SD	111.61*	14.53*	0.26	0.92*	1.24*	1.52*
	25.38	4.83	0.36	0.65	0.77	0.79

*Significantly different from the other technique.

Radial meniscal tears are a source of pain and disability for patients. Their treatment may include debridement of the unstable edge (partial meniscectomy) or meniscal repair. When a radial tear extends through the peripheral fibers, the ability of the meniscus to resist hoop stress is lost, rendering the tissue incompetent. The effect of this injury has been compared with a complete meniscectomy.[1] However, because most radial tears occur within the avascular central third of the meniscus, their ability to heal has been questionable.

Although the treatment of radial meniscal tears is important for patients with mechanical symptoms, repair of these tears may also effectively restore tibiofemoral contact pressures to normal. Bedi et al.[2] showed that large radial meniscal tears (up to 90% of the width) did not significantly increase tibiofemoral contact pressures, but partial meniscectomies did. For this reason, if radial tears can be repaired, it may be possible to preserve nearly normal tibiofemoral contact pressures and minimize the risk of degenerative arthrosis.

Additionally, current repair techniques are not ideally suited to address this pattern of meniscal injury. To address this deficiency, this investigation sought to characterize a new device for repairing radial meniscal tears and to compare this method with the gold standard, the inside-out repair. We hypothesized that repairs with the new all-inside device would result in less gap formation and a higher load to failure than with the inside-out repair. The specimens were tested using custom jigs designed to apply stress perpendicular to the tear to generate the greatest potential displacement.[5] Although this loads the meniscus in only one plane, it creates a “worst case scenario” in which the load applied creates the greatest potential for tear propagation and repair displacement.

Limitations

As with all laboratory investigations, this study has its limitations. Porcine menisci were used as a surrogate for human tissue. Although similar in size and shape to human menisci, the tissue is not a perfect match. Porcine menisci are thicker and denser than human menisci and may not offer as accurate a comparison as sheep menisci.[24] Although our results in porcine menisci are similar to those of Rimmer et al.,[19] their work used a vertical loop in human menisci with a longitudinal tear. The porcine menisci were from pigs of similar age and size and thus were very uniform in shape and material properties, unlike what would be found with donated human tissue. Another consideration is that in this investigation, the menisci were loaded directly to test displacement in one plane. Under physiological conditions, the meniscus is loaded in compression, tension, and shear simultaneously. Unfortunately, the design of this laboratory study does not address how multidirectional loading of the meniscus stresses the repair. The repair knots were tied in an open fashion to eliminate variability between inside-out and all-inside repairs, which are tied arthroscopically. The experience in our laboratory has been that knots tied with the assistance of a knot pusher are tighter and exhibit less displacement than those tied open, and this may have affected the observed outcomes for the all-inside repairs. Finally, as a laboratory study, our results approximate immediate postoperative conditions: a point in time at which no healing has occurred and the repair is most vulnerable.[25,26] Although the all-inside technique resulted in lower displacement at the repair site, what is not currently known is to what degree displacement of meniscal repairs affects clinical outcome and healing.

For meniscal radial tear repairs, the vertical suture configuration created by the all-inside technique resulted in lower displacement, higher load to failure, and greater stiffness compared with the horizontal inside-out technique.

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