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Pull-Out Strength and Stiffness of Meniscal Repair Using Absorbable Arrows or Ti-Cron Vertical and Horizontal Loop Sutures*

Uli W. Boenisch,†‡ MD, Kenneth J. Faber,† MD, Michael Ciarelli,§ PhD, J. Richard Steadman,† MD, and Steven P. Arnoczky,§ DVM

From the †Steadman Hawkins Sport Medicine Foundation, Vail, Colorado, and the §Laboratory for Comparative Orthopaedic Research, Michigan State University, College of Veterinary Medicine, East Lansing, Michigan

ABSTRACT

We tested pull-out strength and linear stiffness of meniscal repair using bioabsorbable arrows and vertical and horizontal loop sutures in fresh-frozen bovine lateral menisci. In phase I, menisci repaired either with 2–0 Ti-Cron vertical or horizontal loop suture, or 10-, 13-, or 16-mm Meniscus Arrows were loaded to failure at 12.5 mm/sec. In phase II, we examined the number of barbs engaged and angle of insertion using 10- and 13-mm arrows. Pull-out strengths of both suture repair groups were significantly higher than those of the arrow groups. Vertical loop sutures were significantly stiffer than horizontal sutures and 10-mm arrows. In phase II, the mean ultimate load to failure for the 10-mm arrows was 35.1 N, significantly stronger than in phase I (18.5 N); however, stiffness remained low (7.9 N/mm). Five arrows in the 13-mm group were inserted parallel to the tibial surface and showed no significant difference from phase I. Five arrows were inserted at more than a 30° angle. This group was significantly weaker than in phase I. Single vertical loop suture showed the highest overall pull-out strength. Although weaker than sutures, arrows should provide sufficient stability for meniscal healing. The number of barbs engaged and angle of insertion are critical.

The first described direct meniscal repair, performed by Annandale[3] in 1885, was ignored until the 1930s when King[10] demonstrated the successful repair of menisci in dogs. Although Fairbank[8] showed that total meniscectomy predictably results in arthritis, routine repair of meniscal lesions was largely ignored in the past. Over the past 50 years surgeons have recognized that the menisci are vital, integral components for normal knee function. The menisci participate in tibiofemoral load transmission,[12] shock absorption,[19] lubrication,[13] and passive stabilization of the knee joint.[9] In the 1980s, Arnoczky and Warren[4,5] defined the limits of meniscal vascularity. Their results, along with the orthopaedic community's growing experience in arthroscopic techniques of meniscal repair, have led to the present concept of preserving as much meniscal tissue as possible. Excellent results have been obtained in the repair of peripheral vertical tears in the red-on-red zone.[17] Meniscal repair can be performed through an arthrotomy or by various arthroscopic techniques, including the inside-out technique, the outside-in technique, and the all-inside technique.

The all-inside meniscal repair with bioabsorbable polylactic acid arrows is appealing because it simplifies operative techniques and minimizes neurovascular complications. Albrecht-Olsen et al.[1] designed the first absorbable arrows and instrumentation, and these were first used in a patient in 1992. The pull-out strength for arrows compared with suture repair has been reported by Albrecht-Olsen et al.[2] and Dervin et al.[7] Albrecht-Olsen et al.[2] investigated a single arrow length and compared its pull-out strength with that of a horizontal mattress suture in bovine cadaveric menisci. Dervin et al. tested 13-mm arrows and vertical loop suture repair in human cadaveric knees. No information is available that suggests the number of barbs (and therefore the arrow length) crossing the repair site and the angle of arrow insertion influence the strength of the meniscal repair. No data have been published on linear stiffness (ability to resist deformation) of meniscal repair.

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‡ Address correspondence and reprint requests to Uli W. Boenisch, MD, Von Osten Strasse 11, 86199 Augsburg, Germany.

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The purposes of this in vitro study on bovine lateral cadaveric menisci were 1) to compare pull-out strength and linear stiffness of 2–0 Ti-Cron (Sherwood-Davis & Geck, St. Louis, Missouri) vertical loop and horizontal loop suture and 10-, 13-, and 16-mm Meniscus Arrows (Bionx Implants, Inc., Blue Bell, Pennsylvania); 2) to determine whether the pull-out strength of arrow repair depends on the number of barbs that lie beyond the lesion; and 3) to determine whether the angle of arrow insertion is critical for pull-out strength.

MATERIALS AND METHODS

Seventy fresh-frozen bovine menisci were used for the pull-out study in two phases. The menisci were harvested from the meniscosynovial junction of 24-month-old steers. They were all lateral menisci and were wrapped in normal saline-soaked gauze and then frozen at −20°C.

The material properties of bovine meniscus are well described by Proctor et al.[14] Its structure serves as an ideal model to test pull-out strength and stiffness of fixation devices. Using lateral bovine menisci of the same age assures more uniform biomechanical properties. The age-related differences in structural properties of human cadaveric menisci are eliminated.

After thawing, a complete, longitudinal, vertical laceration was created in the middle third of each meniscus with a scalpel. A custom-made template was used to mark the location of the laceration and the size of the meniscal segment used for testing. The template ensured a proper fit in the testing jig. Care was taken to make a complete anterior to posterior laceration to prevent any load transfer through the meniscus other than at the repair site.

Fifty menisci were used in phase I. The laceration was made 1 cm from the peripheral meniscosynovial rim to ensure that even the longest arrow did not protrude more than 1 mm beyond the meniscosynovial junction. The two sections of the menisci were reduced anatomically and connected only by the repair devices (Fig. 1, A through C).

Ten menisci each were repaired using a 2–0 Ti-Cron suture with a single vertical loop stitch technique (Fig. 1A) or a horizontal loop stitch technique (Fig. 1B). The suture was inserted into the meniscus, passing 5 mm into the medial portion of the meniscus central to the tear. Three locked knots were tied on the capsular side of the meniscus. Ten specimens each were repaired using Meniscus Arrows of 10, 13, and 16 mm length (Fig. 1C).

The arrows are T-shaped with perpendicular barbs. They are made of biodegradable polylactic acid and consist of a T-head (4 mm) and a stem of 1.1 mm diameter. The number of barbs ($N = 10$) is the same for the various-sized arrows. The 10-mm arrow is fully barbed, whereas the 13- and 16-mm arrows have a smooth shaft of different lengths, 3 or 6 mm, thus leaving more barbs beyond the repair site. The stem penetrates the meniscus and the barbs are caught by the circumferential fibers of the peripheral part of the meniscus. The T-head keeps the central part of the meniscus in proximity to the periphery.

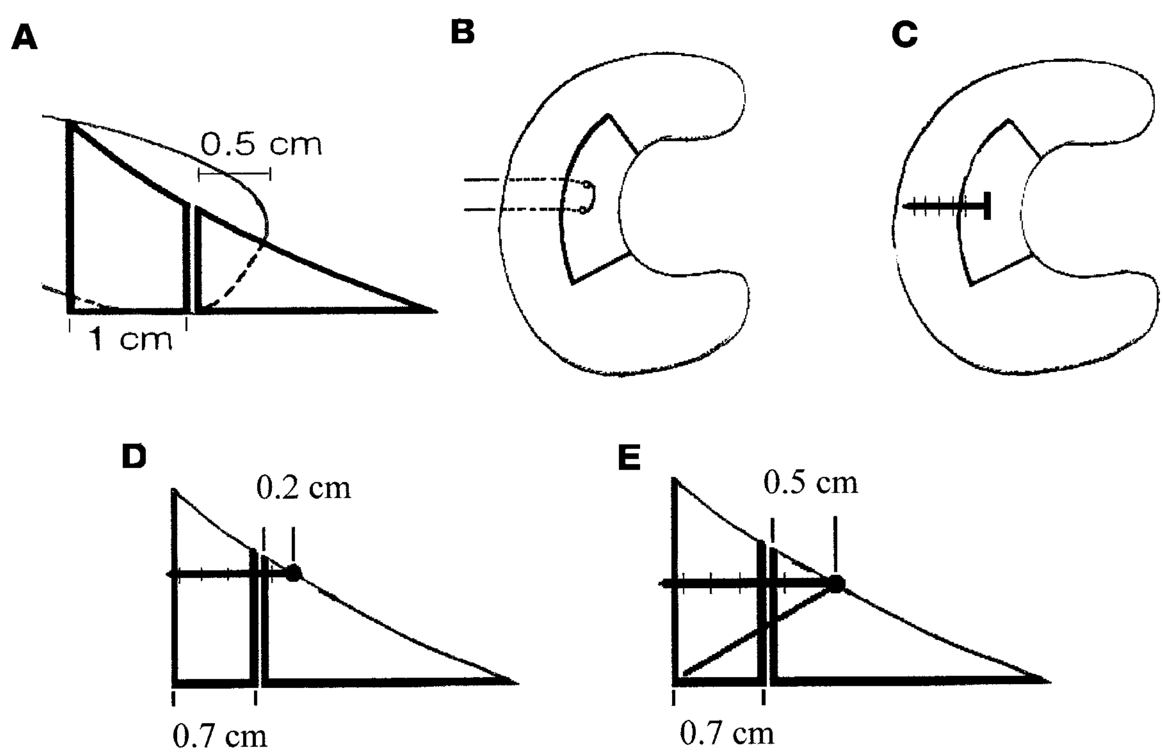

Figure 1. In phase I, meniscal repair was performed with vertical suture loop (A), horizontal suture loop (B), or Meniscus Arrow (C). In phase II, the repair site was changed (D) and the angle of insertion was changed (E).

The surgical technique was as follows. The created meniscal lesion was reduced anatomically. A toothed cannula was positioned 5 mm central to the meniscal lesion, and perpendicular to it. In phase I care was taken to choose an insertion angle parallel to the tibial surface of the meniscus and "loading direction." The arrow was inserted after making a pilot hole in the meniscus with a needle threaded through the toothed cannula. With the cannula in position, the needle was withdrawn and the cannula was loaded with an arrow. The arrow was then advanced into the channel with a blunt pusher, making sure that the T-head was buried parallel to the superior meniscal surface. The orientation of the T-head was therefore parallel to the circumferential fibers.

Twenty menisci were used in phase II. The laceration was made 7 mm from the peripheral meniscosynovial rim so that all devices in phase II protruded 1 mm at the meniscosynovial junction (Fig. 1D). Ten menisci were repaired using 10-mm arrows. In this phase the arrow was inserted only 2 mm central to the laceration, again parallel to the tibial meniscal surface and perpendicular to the lesion as described earlier. Moving the insertion point closer to the lesion (2 mm versus 5 mm in phase I) simply engaged more barbs beyond the laceration.

Ten menisci were repaired using 13-mm arrows. These 10 menisci were divided in two groups of 5. Five menisci were repaired exactly as described in phase I, 5 mm central to the laceration and parallel to the tibial meniscus surface (Fig. 1E). The other five menisci were repaired by inserting the arrow 5 mm central to the laceration; however, the arrow was angled 30° toward the tibial meniscal surface (Fig. 1E).

The peripheral section of each specimen was placed in a custom-designed meniscal clamp, and the central section was placed in a grip. Each specimen was immersed in a saline bath (at room temperature) and mounted on a materials testing machine (Instron 8501M, Materials Testing System, Instron Corp., Canton, Massachusetts) equipped with a 25-pound load cell (Sensotec, Columbus, Ohio). Each repaired meniscal segment was loaded parallel to the tibial-side surface of the meniscus. Load-to-failure testing was performed at a constant displacement rate of 12.5 mm/sec. The displacement rate was consistent with prior studies evaluating the ultimate pull-out strength of suture anchors and is reflective of rapid loading forces. The devices were tested to failure. The data acquisition and analysis were performed on a personal computer. Mode of failure for each test (pull-out, pull-through, knot slippage, or suture breakage) was recorded on individual data sheets. Suture failure occurred as suture breakage at the junction of the knot or as knot slippage. The arrows failed by pull-out of the barbs from the peripheral meniscal section or by pull-through of the T-head through the central meniscal section. All trials were video recorded.

In phase II, the number of barbs engaged in the peripheral segment of the meniscus was determined. The angle of insertion was evaluated and pull-out strength was correlated with the number of engaged barbs.

Data Analysis

Ultimate load to failure was evaluated. Linear stiffness was defined as the linear portion of the load-deformation curve. Analysis of variance and Tukey's post hoc test were used to determine differences between the groups tested, that is between the 10-, 13-, and 16-mm arrows and the vertical and horizontal sutures. Significance was determined at $P < 0.05$.

RESULTS

Phase I

In phase I, one specimen was excluded from the data analysis. This specimen was repaired with a 16-mm arrow that did not enter into the peripheral channel and, as a result, the arrow underwent deformation. This specimen was excluded from the final statistical analysis, leaving 9 specimens in the 16-mm arrow group and 10 specimens each for the vertical loop suture, horizontal loop suture, and 10- and 13-mm arrow groups.

The 2–0 Ti-Cron vertical loop suture was the strongest device with a mean (±SD) pull-out strength of 72.4 ± 9.2 N (range, 57.2 to 83.7), followed by 2–0 Ti-Cron horizontal loop suture with 68.3 ± 9.5 N (range, 48.7 to 83.3). There was no significant difference between the suture groups. The 16-mm arrows showed a mean pull-out strength of 52.7 ± 11.2 N (range, 39.9 to 74.7). Specimens repaired with 13-mm arrows had a mean pull-out strength of 39.4 ± 10.3 N (range, 18.5 to 53.3). The weakest mean pull-out strength was measured for the 10-mm arrow group, with 18.5 ± 9.9 N (range, 5.3 to 38.0). The pull-out strengths were significantly different between each arrow group. Each arrow group was also significantly different from each suture group.

Linear stiffness was calculated from the linear portion of the load-deformation curve. Vertical suture fixation was stiffest with 11.7 ± 3.1 N/mm (range, 8.3 to 16.9), followed by the 16-mm arrows at 10.5 ± 1.9 N/mm (range, 6.6 to 13.3), and the 13-mm arrows at 10.0 ± 2.8 N/mm (range, 6.3 to 16.5). Stiffness of the horizontal sutures, 7.7 ± 0.8 N/mm (range, 6.3 to 8.8), was only slightly higher than the 10-mm arrow group with 7.2 ± 3.66 N/mm (range, 3.8 to 15.7). There was a significant difference between stiffness of vertical and horizontal sutures and between the vertical sutures and 10-mm arrows. There was no significant difference between the stiffness of each arrow group.

The mechanisms of failure in the suture groups were suture failure at the junction of the knot in nine cases and knot slippage in one case. Failure mechanisms for the arrow groups were as follows: Pull-out of the barbs from the peripheral meniscal section in 18 cases, and pull-through of the T-head through the central meniscal section in 11 cases. However, the mode of failure differed between the arrow groups. In the 10-mm arrow group, 9 of 10 specimens failed by pull-out and 1 failed by pull-through. In the 13-mm arrow group eight failed by pull-out and two by pull-through, while in the 16-mm arrow group only one failed by pull-out and eight failed by pull-through.

Phase II

In phase II, one specimen of the 10-mm arrow group was excluded from data analysis for the same reason as described for one 16-mm arrow in phase I. One specimen of the 13-mm arrow group with angled insertion was accidentally introduced at an angle <30° toward the tibial meniscal surface. It was therefore analyzed in the regular 13-mm arrow group. This left six specimens in the 13-mm arrow group and four specimens in the angled 13-mm arrow group. The 10-mm arrow group had a mean pull-out strength of 35.1 ± 9.9 N (range, 19.6 to 48.7), which was not significantly different from the 13-mm arrow group with 33.1 ± 8.8 N (range, 19.1 to 42.4). The angled 13-mm arrow group showed a pull-out strength of 18.4 ± 8.2 N (range, 8.6 to 28.0), which was significantly less than the 10- and 13-mm arrow groups with straight insertion. No significant difference was seen for stiffness analysis in phase II (10-mm, 7.9 ± 2.6 N/mm [3.6 to 10.3]; 13-mm, 9.5 ± 1.7 N/mm [8.1 to 12.1]; angled 13-mm, 7.3 ± 4.1 N/mm [3.2 to 12.8]). However, the 10-mm arrow group was significantly less stiff than the vertical suture group in phase I.

Pull-out of the barbs from the peripheral meniscal section was the failure mode in 15 cases, and pull-through of the T-head through the central meniscal section occurred in 4 cases. In the 10-mm arrow group in phase II, seven of nine specimens failed by pull-out and two failed by pull-through. In the 13-mm arrow group, four failed by pull-out and two by pull-through, while in the angled 13-mm arrow group all four failed by pull-out. There was no relation between stiffness and failure modes in either test phase.

Comparison of Phase I and Phase II

Pull-out strength of 10-mm arrows in phase II was significantly higher than in phase I (35.1 N versus 18.5 N). No significant difference was found for the 13-mm arrow groups. However, if the arrow was angled 30° toward the tibial meniscal surface, the difference between the 13-mm arrow groups was significant (33.1 N for arrows with straight insertion in phase II versus 18.4 N for arrows with angled insertion). There was no statistical difference in stiffness between tests in phase I and phase II in the arrow group. However, there was a significant difference between 10-mm arrows in phase II and horizontal and vertical suture repair from phase I.

In phase II the number of barbs engaged in the peripheral meniscal section was counted after load to failure testing. An average of six barbs were engaged for all groups (10-mm arrow, 13-mm arrow, and 13-mm angled arrow). Although six barbs were engaged in both 13-mm arrow groups, the angled arrows were significantly weaker than arrows inserted parallel to the tibial meniscal surface and loading direction.

DISCUSSION

Kohn and Siebert[11] investigated meniscal suture techniques in intact medial menisci from human cadavers using a single suture. They found a pull-out strength of 105 N for vertically placed sutures and recommended a vertical single loop placement for open meniscal repairs. With regard to the two most common arthroscopic methods of suture placement, they found that horizontal mattress sutures had higher tearing stresses than the knot-end technique described by Warren,[20] and they recommended horizontal placement for arthroscopic repair. However, their study did not model a system with a meniscal lesion, and the clinical implication of this study is questionable. Raunest and Derra[15] investigated the biomechanics of the repaired meniscus but studied only load transmission and radial strain. They did not attempt to analyze the failure strength of these systems. They found vertical suture repair to be markedly better than horizontal suture repair. Rimmer et al.[16] investigated lateral human cadaveric menisci and reported a pull-out strength of 67 N for a vertically placed single loop repair; the mode of failure was suture breakage. For horizontal sutures the pull-out strength was only 29.3 N, and the suture pulled through the center part of the repair.

Since the advent of Meniscus Arrows, several reports have compared arrows with suture repair. Dervin et al.[7] compared 2–0 Ethibond vertical loop suture (Ethicon, Inc., Sommerville, New Jersey) with 13-mm Meniscus Arrows in human cadaveric menisci and found a pull-out strength of 58.3 N for the sutures and 29.6 N for the arrows. The strength of the arrows was similar to that of the horizontal mattress repair in the study by Rimmer et al. However, the position of the arrow in this setup allowed the engagement of only a few barbs in meniscal tissue. Most of the barbs were engaged in capsular perimeniscal tissue. Albrecht-Olsen et al.[2] reported on results of horizontal mattress repair and 13-mm arrows in bovine meniscal tissue and found no significant difference between pull-out strength of suture (49 N) and 13-mm arrow (53 N). These studies used very slow displacement rates of 5 mm/min[7] and 50 mm/min.[2]

The advantage of our study was that we used age-matched bovine menisci and thus eliminated the highly variable degenerative components of human cadaveric menisci. We also used a displacement rate of 12.5 mm/sec, which has been used previously to determine suture anchor strength and is likely more reflective of an in vivo loading force. Finally, we determined the effect of different arrow lengths on the mean load to failure. The questions of whether vertical suture technique is superior to horizontal suture was also addressed as well as stiffness of each device.

The strongest repair device in this study was the suture repair. No significant difference was seen between the pull-out strength of horizontal or vertical sutures. A pull-out strength of 72.4 N for vertical sutures in our series was similar to the 67 N found by Rimmer et al.[16] in human cadaveric menisci. The pull-out strength for the horizontal sutures in our series, however, was twice as high as that in the Rimmer et al. series (68.3 N versus 29.3 N). Horizontal sutures may be more sensitive to the heterogeneity of human cadaveric menisci samples, but this remains speculative.

Our series could not show that a single vertical loop suture is superior to a horizontal mattress suture, considering the maximum load to failure of a single suture as judgment for successful repair alone. However, stiffness of a repair should be considered as well. Vertical suture repair had a significantly higher stiffness than horizontal suture repair and 10-mm Meniscus Arrow repair. The predominance of semicircular-oriented fibers in meniscal tissue, which are better captured in a vertical suture, may be an explanation for the higher stiffness of vertical sutures.[6] Based on these data, we support the biomechanical results of Raunest and Derra,[15] that vertical sutures are better than horizontal sutures.

The pull-out strength of 2–0 Ti-Cron vertical and horizontal loop repair was significantly higher than that of each arrow group in phase I. A significant difference was also demonstrated between each of the three arrow groups in phase I. The mean pull-out strength of 18.5 N for 10-mm arrows was well below the results reported on meniscal repair in previous studies. The results for 13-mm arrows were higher than in the series reported by Dervin et al.[7] but lower than in the Albrecht-Olsen report.[2] The 16-mm arrows had results similar to 13-mm arrows in Albrecht-Olsen's paper (52.7 N versus 52.7 N). Both the 13-mm and the 16-mm arrows were stronger than horizontal mattress sutures.[16]

We clearly demonstrated that the number of barbs engaged beyond the meniscal tear and the angle of insertion were crucial for the fixation strength. In phase I, we inserted the arrows and sutures 5 mm central to the meniscal laceration. The design of a 10-mm arrow with a fully barbed shaft theoretically allowed only 2 to 3 barbs to be engaged in the peripheral meniscal section. This probably resulted in the low pull-out strength of this device. A 13-mm arrow, with its 3-mm smooth shaft, allowed more, but not all, barbs to be engaged. The statistically significant difference between the 10- and 13-mm arrows in phase I led to the conclusion that the more barbs that are engaged, the higher the pull-out strength. This was backed up by the results of the 16-mm arrow group. The smooth shaft of a 16-mm arrow is 6-mm long, and all barbs were probably engaged in the peripheral section of the meniscal tear. This was reflected by the pull-out strength of 52.7 N, which was significantly superior to that of the 10- and 13-mm arrow groups. The statistical analysis was also reinforced by the macroscopic observations during testing. While 9 of 10 arrows pulled out from the peripheral section of the meniscus in the 10-mm arrow group, only 1 of 9 pulled out from the peripheral section in the 16-mm arrow group. The remainder failed by pull-through of the T-head through the central section of the repaired meniscus.

Phase II was designed to prove our conclusions regarding the barb engagement. We also tested the consequences of angled arrow insertion. After load-to-failure testing, the number of barbs that were engaged was counted for 10-mm arrows, 13-mm arrows inserted straight, and 13-mm arrows inserted at an angle. By moving the 10-mm arrow insertion closer to the laceration (2 mm versus 5 mm in phase I), we simply engaged more barbs beyond the laceration and increased the maximum load to failure significantly compared with phase I. An average of six barbs were engaged beyond the lesion. A mean pull-out strength of 35.1 N for the 10-mm arrows in phase II was significantly stronger than for the 10-mm arrows in phase I (18.5 N) and was not statistically different from the pull-out strength of 13-mm arrows in phase I (39.4 N) and phase II (33.1 N) (inserted 5 mm central to the lesion, average of six barbs engaged as well). These data support our conclusion about barb engagement of phase I. Figure 2 shows a linear correlation between the number of barbs engaged and the pull-out strength for the 10- and 13-mm arrow in phase II. However, stiffness of the 10-mm arrow repairs was as low as for a horizontal suture repair.

Based on this study, we believe that angled arrow insertion should be avoided. Although six barbs were engaged beyond the lesion in phase II, the pull-out strength of 18.4 N for the angled 13-mm arrow was as weak as the results for 10-mm arrow repair in phase I. Because of the insertion angle, the barbs seem not to sufficiently capture the circumferential fibers of the meniscus. Further testing may be needed to more carefully examine this relationship.

The mean pull-out strength of 10- and 13-mm arrow repair was significantly lower than that of the vertical loop and horizontal loop suture repairs. However, no study has shown how high the pull-out strength needs to be to keep the meniscus in place under clinical conditions. We also point out that this study tested only one suture or one arrow, but clinical repair invariably uses multiple sutures or arrows. Although vertical loop sutures are recommended for meniscal repair now, many papers have been published reporting good results with horizontal mattress suture repair, in which the pull-out strength closely resembles that for the Meniscus Arrow.[6,16–18] We do not believe that the decreased pull-out strength with arrow repair reduces meniscal healing rates in vivo. Our own clinical experience with well over 100 meniscal arrow repairs are encouraging. Kristensen (personal communication), in a randomized controlled study, reported that ar-

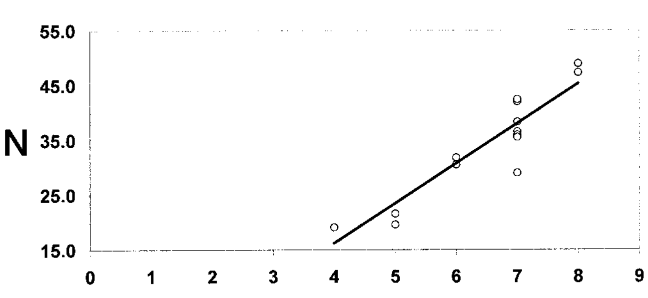

Figure 2. Correlation between engaged barbs per tested arrow (open circles) and pull-out strength (in newtons) in phase II.

rows have a success rate similar to that of suture repair. Based on our data from this in vitro study, we speculate that the biomechanical properties of all arrows are sufficient to provide stability to permit meniscal healing in a manner similar to suture repair. An arrow length should be selected that allows for the maximum number of barbs to be engaged in the peripheral portion of the meniscus, beyond the meniscal lesion. The arrow should be inserted parallel to the tibial meniscal surface and perpendicular to the lesion.

SUMMARY

1. Single vertical loop suture repair had the highest pull-out strength and was significantly stronger than meniscal repair performed with arrows. Stiffness of the vertical sutures was also highest, but was not significantly different from meniscal repair with arrows.

2. Single horizontal loop suture was not weaker than vertical suture; however, it had significantly lower stiffness. It is therefore biomechanically less favorable for meniscal repair.

3. A significant difference in pull-out strength existed between the different-sized arrows. The 16-mm arrows were strongest and the 10-mm arrows were weakest.

4. Pull-out strength of 10-mm arrows can be increased by inserting the arrow as close as possible to the meniscal lesion. However, stiffness of the repair remains low.

5. In meniscal repair with arrows, the maximum number of barbs should be engaged beyond the meniscal tear. This can be achieved either by using a 16-mm arrow or by moving the location of insertion of a 13-mm arrow into the central part within 3 mm of the edge of the tear or a 10-mm arrow to within 2 mm of the tear.

6. Angled arrow insertion should be avoided.

7. Arrows most likely provide adequate stability for meniscal healing.

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