Performance Comparison of a Pretied Suture Knot With Three Conventional Arthroscopic Knots

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Purpose: To compare the knot characteristics of a pretied suture knot with 3 of the most commonly used arthroscopic knots tied with various high-strength sutures. Methods: Three commonly used arthroscopic knots (surgeon’s knot, Seoul Medical Center, and Duncan loop) tied with no. 2 high-strength sutures were compared with a pretied knot secured with either 1, 2, or 3 reversed half hitches (RHAPS). An orthopaedic sports medicine surgeon and fellow tied a total of 120 knots. All knot combinations were tested for strength, knot bulk, cyclic loop elongation, ultimate loop elongation, and ultimate strength. Results: All pretied configurations had statistically significant improved strength (P = .048, P ≤ .001, and P < .001) versus all other knot groups with mean ± standard deviation loads of 206.3 ± 37.5, 285.6 ± 68.6, and 357.6 ± 61.1 N, respectively. The pretied knot with 1, 2, or 3 RHAPS has significantly smaller volume than the arthroscopic knots in all suture materials. All pretied knot configurations demonstrated no significant difference in cyclic loop elongation compared with standard arthroscopic knots; however, they had a statistically significant lower ultimate loop elongation (P = .001 for each pretied knot configuration). Conclusions: Compared with other commonly tied arthroscopic knots using no. 2 high-strength suture, the pretied knot with doubled no. 1 high-tensile-strength suture tied with 1, 2, or 3 RHAPS results in a statistically significantly improved strength. The pretied knot has an equivalent cyclic loop elongation and lower ultimate loop elongation with all RHAP configurations. The pretied knot with 2 or 3 RHAPS has a significantly higher ultimate strength than all combinations of arthroscopic knots excluding one. The pretied knot with 1, 2, or 3 RHAPS has significantly less knot volume than all other knots tested and offers a more reproducible knot. Clinical Relevance: The pre-tied knot offers equivalent or improved strength while having a smaller knot volume.
high-strength sutures. We hypothesized that the pretied knot would be stronger and have smaller mass.

**Methods**

Proknot, a doubled no. 1 Permacord suture\(^1\) with a proprietary pretied sliding knot (Proknot Technology, DePuy Synthes Mitek Sports Medicine, Raynham, MA), was compared with the Duncan loop, Seoul Medical Center (SMC), and surgeon’s knot. These 3 commonly used arthroscopic knots were chosen to represent sliding, sliding-locking, and static knot configurations, and their frequency of use was confirmed on the basis of a survey of sports medicine surgeons.\(^7\) Each arthroscopic knot was tied using 3 commercially available no. 2 high-strength sutures (Orthocord, DePuy Synthes Mitek Sports Medicine, Raynham, MA; FiberWire-Arthrex, Naples, FL; and MaxBraid-Biomet, Warsaw, IN). All knots were tied as shown in Figure 1 and backed up with 3 RHAPs to maximize knot security.\(^8,22\) Proknot was tied and then secured with 1, 2, or 3 RHAPs.

Pilot studies were conducted on knot strength, which indicated that the standard deviation (SD) of knot strength was approximately 25 N. A power analysis having a target power of 0.8 and a significance level \(\alpha = 0.05\) established that 10 samples from each group would be required to show a difference of 48 N.

An orthopaedic sports medicine surgeon (P.J.F.) and an orthopaedic sports medicine fellow (S.A.R.) tied all sutures around an 8-mm acetal rod. Each surgeon tied an equivalent number of knots with each suture. Using disposable, latex-free surgical gloves, all knots were tied through arthroscopic cannulas using an arthroscopic knot pusher to simulate an arthroscopic environment (Clear Cannula System and Knot Pusher, DePuy Synthes Mitek Sports Medicine, Raynham, MA). While on the rod, all knots were photographed for subsequent digital volumetric calculation.

The 8 mm diameter acetal rod provided reference for absolute scaling of length dimensions within each image, for height (h) and diameter (d) of the knot (Fig 2; Photoshop CS5, Adobe Systems, San Jose, CA).\(^23-25\) As in other studies of knot volume, a simplification of bulk knot geometry was used.\(^26\) Here the form of each knot was assumed to be generally cylindrical, with volume \(V\) as follows: \(^{27}\)

\[
V = \frac{\pi d^2 h}{4}.
\]
The tied suture loops were removed from the rod, immersed in saline, and placed on shackles using two parallel rods with no part of the knot contacting the rods. After mounting on a servohydraulic machine (MTS, Eden Prairie, MN), the suture loops were pretensioned to 5 N, and then 500 sinusoidal load cycles were applied at 27.5 ± 17.5 N at a rate of 1.0 Hz. After a 10-second ramp down period, the samples were loaded to tensile failure at a rate of 1 mm/second. Consistent with previous studies, we chose 3 mm to define failure.28

Statistical Analysis
One-way, unstacked analyses of variance were used to compare the different test groups for loop elongation during cycling, peak load at 3 mm displacement, ultimate failure load, ultimate failure displacement, and knot volume. Two-way Student’s t-tests were used to make comparisons between pairs of test groups tied by both surgeons for clinical strength. Knot samples were excluded for the following reasons: knot breakage or fraying, knots incorrectly tied, knots damaged during removal from rod, or any complications with the load frame.

Results

Peak Load at 3 mm Displacement
All configurations (1, 2, or 3 RHAPs) of the pretied knot had a statistically significant higher (P = .048, P < .001, and P < .001) peak load at 3 mm displacement versus all other knot groups, with mean (±SD) loads of 206.3 ± 37.5, 285.6 ± 68.6, and 357.6 ± 61.1 N, respectively (Fig 3). The standard arthroscopic knot with the highest clinical strength was the surgeon’s knot using MaxBraid (169.6 ± 81.1 N).

Intersurgeon Variability
There was a statistical difference in the mean clinical strengths between the two surgeons (159.9 v 132.8 N; P = .005). However, for each of the pretied knot configurations, a difference between the two surgeons could not be detected (3 half hitches [HH] P = .882, 2HH P = .694, 1HH P = .883).

In a series of two-sample t-tests, clinical knot strength, knot bulk, loop elongation during cyclic loading, ultimate loop elongation, and ultimate strength were compared between operators for Proknot +1HH, +2HH, and +3HH. Among the 15 operator-to-operator pairwise comparisons, no statistical difference could be detected for any of the parameters evaluated between surgeons.

Ultimate Load to Failure
The pretied knot with 2 and 3 RHAPs (286.25 ± 67.6 and 361.3 ± 65.2 N) and SMC with MaxBraid (259.49 ± 49.2 N) had a statistically significant higher ultimate load to failure than all other knots. There was no statistical difference between any of the remaining knots when compared with each other (P = .295). The Proknot with 1 RHAP had an ultimate load to failure of 206.5 ± 37.5 N.

Ultimate Displacement
There was a statistically significant difference in ultimate displacement between all surgeon-tied knots and each of the pretied knot configurations (P = .001).
There was no difference among the 3 configurations of the pretied knot (3 HH 2.38 ± 0.48, 2 HH 2.47 ± 0.51, 1 HH 2.49 ± 0.47 mm). There was no difference detected among any of the surgeon-tied knots ($P = .12$).

**Loop Elongation with Cyclic Loading**
SMC and Duncan loop tied with MaxBraid had a significantly higher cyclic loop elongation when compared with all other knot combinations ($P < .001$ and $P = .004$). The pretied knot with 1, 2, and 3 RHAPs had loop elongations of 0.79 ± 0.36, 0.66 ± 0.41, and 0.42 ± 0.07 mm, respectively.

**Knot Volume**
No statistical difference could be detected in the knot size of the pretied knot +1HH, +2HH, or +3HH ($P = .372$). The pretied knot in all configurations was significantly smaller than all surgeon-tied arthroscopic knots (Fig 4). On average, the Proknot +1HH was 53% of the size of the surgeon’s knot with Fiberwire (statistically smaller, $P = .045$) and 27% of the size a Duncan loop with Fiberwire (statistically smaller, $P < .001$). The surgeon’s knot and Duncan loop tied with Fiberwire were the standard arthroscopic knot and suture combinations, having the smallest and largest average knot size, respectively.

**Mode of Failure**
The mode of failure was identified for each knot configuration (Table 1). In the conventional arthroscopic knots, two modes of failure were observed: knots that slipped or sutures that broke. For the pretied knot, in addition to the 2 modes of failure described above, the third mechanism was the half-hitch(es) pulling through the sliding knot (Fig 5).

**Discussion**
The pretied knot displayed decreased gap formation, smaller knot bulk, comparable loop elongation, and similar ultimate strength when tested against common

![Image of bar graph](4. A. RODES ET AL.)

*Significant difference observed against other test groups.

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**Fig 4.** Knot volume created by each knot. Error bars represent standard deviation. (FW, Fiberwire; HH, half hitch; MB, MaxBraid; OC, Orthocord; SMC, Seoul Medical Center.)

**Table 1.** Mode of Failure of Knots (Sample Size = 10 in Each Test Group)

<table>
<thead>
<tr>
<th>Knot Type</th>
<th>Suture Type</th>
<th>Knot Slipped</th>
<th>Suture Break</th>
<th>Half-Hitch Slip-Through (Proknot Only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duncan loop</td>
<td>No. 2 Fiberwire</td>
<td>10</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>Duncan loop</td>
<td>No. 2 MaxBraid</td>
<td>3</td>
<td>7</td>
<td>—</td>
</tr>
<tr>
<td>Duncan loop</td>
<td>No. 2 Orthocord</td>
<td>7</td>
<td>3</td>
<td>—</td>
</tr>
<tr>
<td>Proknot +1HH</td>
<td>No. 1 Permacord</td>
<td>4</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Proknot +2HH</td>
<td>No. 1 Permacord</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Proknot +3HH</td>
<td>No. 1 Permacord</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>SMC</td>
<td>No. 2 Fiberwire</td>
<td>10</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>SMC</td>
<td>No. 2 MaxBraid</td>
<td>5</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>SMC</td>
<td>No. 2 Orthocord</td>
<td>8</td>
<td>2</td>
<td>—</td>
</tr>
<tr>
<td>Surgeon’s knot</td>
<td>No. 2 Fiberwire</td>
<td>9</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Surgeon’s knot</td>
<td>No. 2 MaxBraid</td>
<td>5</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>Surgeon’s knot</td>
<td>No. 2 Orthocord</td>
<td>8</td>
<td>2</td>
<td>—</td>
</tr>
</tbody>
</table>

HH, half hitch; SMC, Seoul Medical Center.
arthroscopic knots. Knot configuration, surgeon knot-tying experience, suture choice, and location of knots relative to the articular surfaces are several factors that contribute to the success of the procedure. Optimizing those variables may lead to more favorable clinical outcomes.

Minimizing gap formation between soft tissue and prepared bone is paramount to healing. Most arthroscopic knots are tied through cannulas and require surgeons to create an extracorporeal base knot, advance it to the soft tissue, and then secure it with a series of half hitches. The importance of properly created half hitches, reversing both the post and direction of wrapping loops, has been reported elsewhere. Incorrectly delivered half hitches may result in poor knot security. Improperly applied tension on either the post or wrapping strand during half hitch formation may lead to poor loop security and suboptimal apposition of soft tissue to bone.

There is no consensus on the optimal arthroscopic knot. Several studies have shown that the Duncan loop has decreased strength characteristics compared with other arthroscopic knots. Swan et al. showed that both the surgeon’s knot and SMC had higher resistance to single load to failure and cyclic failure to 3 mm displacement with both FiberWire and MaxBraid when compared with the Duncan loop. Barber et al. also showed the SMC to have a higher ultimate load to failure and higher cyclic loading to failure. Studies by Dahl et al. and Elkousy et al. also validated these results, showing decreased loop and/or knot security when the Duncan loop was compared with SMC or other knots. However, Miller et al. contradicted these results by revealing the Duncan loop to be equivalent in terms of ultimate load to failure and significantly better at resisting cyclic loading than the SMC knot.

Consistent with the literature, we chose 3 mm of gap formation to define failure. The pretied knot with 1, 2, or 3 RHAPs had a statistically significant higher strength compared with all other knot groups. Equally important was the decrease in loop elongation that is determined during the cyclic loading portion of the testing and most closely represents expected, in vivo physiological forces. The SMC and Duncan loop knot tied with MaxBraid had higher cyclic loop elongation than all other knots, including Proknot. There was no difference between the remaining knots. Several potential explanations exist for the improved results with Proknot.

**Knot Design**

Proknot has some features that make it fundamentally different from other arthroscopic knots. Attached to a suture anchor, the pretied knot is constructed from a no. 1 Permacord suture (braided Blue ultra-high-molecular-weight polyethylene [UHMWPE]) with a premanufactured sliding knot located midlength and temporarily held open by a suture card. This type of knot construct has similar properties to a racking hitch.
knot, which has been investigated previously.\textsuperscript{29} After retrieving the suture through the tissue, the suture is passed through the open sliding knot (Fig 6) and disengaged from the card. The suture is threaded into the knot pusher that is used to deliver the knot to the soft tissue. The desired number of half hitches is placed to secure the knot (Fig 7).

In a standard arthroscopic base knot, the post is a single limb. The subsequent half hitches must incorporate both the post limb and the wrapping limb from the base knot. As demonstrated in our results, one mode of failure is for half hitches to unravel as the knot unravels. The Proknot is constructed with two post limbs. The base knot acts as a noose around those limbs. The subsequent half hitch(es) tied between the post limbs act as a stopper knot, preventing backward translation of the base knot. In this configuration, the backing half-hitches can slip or pull through the base knot. The pull-through mode of failure was seen only in the Proknot group.

**Suture Material**

Three suture materials (FiberWire, Orthocord, MaxBraid) were chosen to represent some of the common high-tensile, abrasion-resistant sutures commonly used in arthroscopic procedures. FiberWire is constructed of a UHMWPE core and a cobraid UHMWPE and polyester sleeve. Orthocord consists of a core of polydiaxanone with a cobraid UHMWPE and polydiaxanone sleeve. Orthocord is coated with caprolactone and glycolide to increase the ease of handling. MaxBraid is composed entirely of UHMWPE.\textsuperscript{9}

Permacord is an uncoated surgical suture made of hollow braid of UHMWPE. As described in the patent, “when a surgeon’s knot is tied with the suture, the cross-sectional shape of the braid collapses upon itself and is reduced in size in response to pressures experienced when the knot is tightened. The resulting knot is a low profile knot that resists slippage.”\textsuperscript{21}

Suture characteristics are contributing factors to knot performance, and similar to knot choice, there is no consensus on the ideal suture or diameter for arthroscopic labral repair. Several studies have shown that no. 2 polyblend sutures are superior to no. 2 Ethibond (Ethicon, Somerville, NJ) sutures in terms of knot security and ultimate tensile strength.\textsuperscript{5,6,8,10,13} Polyblend sutures are the most prevalent sutures in anchors used for labral repair. However, there have been contradictory published results while testing the various polyethylene-based sutures. Swan et al. showed MaxBraid to be superior to FiberWire in load to ultimate failure as well as cyclic loading.\textsuperscript{13} Ilahi et al. showed no statistically significant difference in performance between FiberWire and Orthocord with regards to load to 3 mm displacement.\textsuperscript{6} However, a study by Barber et al. showed a greater tensile strength with FiberWire than with either Orthocord or MaxBraid.\textsuperscript{10} Miller et al. published a study comparing FiberWire, MaxBraid, and Orthocord.\textsuperscript{9} There was no difference in ultimate load to failure among the 3 suture types, although FiberWire had a higher resistance to cyclic loading than Orthocord or MaxBraid. In our study, the doubled-over, uncoated UHMWE no. 1 Permacord incorporated into a pretied knot provided greater strength than the other single-post sutures.

Using a knot with a smaller suture may be clinically advantageous. Several studies have investigated arthroscopic knot height or bulkiness.\textsuperscript{5,11,12} Both knot stack size and proximity to the articular cartilage have been reported to contribute to adjacent chondral damage and have even been implicated in PAGCL.\textsuperscript{3,14,20} Ilahi and his coauthors performed one of the first studies to focus on the bulkiness of arthroscopic knots. They reported significantly smaller knot heights with Orthocord and Ethibond compared with FiberWire and similar knot heights for the Duncan loop, SMC, and surgeon’s knot (4.8, 4.3, and 4.1 mm, respectively).\textsuperscript{6} Hassinger et al. demonstrated significantly smaller knot mass with the SMC knot versus the Duncan loop (7 v 13.2 mg, respectively), and the SMC was one of the smallest of 10 knots compared in that study.\textsuperscript{12}

Knot size has been investigated in previous studies.\textsuperscript{6,11,12} Our study used an established technique for estimating knot volume.\textsuperscript{23} No statistical difference could be detected
in any of the 3 Proknot configurations. On average, the Proknot with one half hitch was 53% of the size of the surgeon’s knot with Fiberwire and 27% of the size a Duncan loop with Fiberwire. Both achieved statistical significance. As Ilahi et al. described, most arthroscopic knots are slip knots, which makes them larger and bulkier when compared with traditional square knots, which are flat. The design of the Proknot allows the base knot to be significantly smaller, and the cinching characteristics with a smaller diameter, hollow suture are key contributors to the decreased volume.

Tying a successful sliding knot requires the creation of a base knot that is secured by a series of half hitches with alternating posts. The importance of properly created half hitches and their contribution to knot strength is well described. Without adequate understanding or careful attention, the surgeon may intentionally or inadvertently create a series of granny knots (wrapping loops created in the same direction around the same post). If so, resultant knot strength will be decreased. This study suggests that the Proknot could be considered a technique-independent knot. The addition of 1, 2, or 3 half hitches significantly decreased gap formation, although more than one half hitch was not required to achieve adequate clinical strength.

This study had 2 orthopaedic surgeons (an orthopaedic sports medicine fellow with 1 year of knot-tying experience compared with a fellowship-trained sports medicine surgeon with 14 years of knot-tying experience). There was a statistically significant difference in mean clinical strengths of standard knots between the two surgeons (experienced, 159.9 N, fellow, 132.8 N). However, among the 15 operator-to-operator pairwise comparisons for Proknot, no statistical difference could be detected for any of the parameters evaluated. These findings suggest that for Proknot, the configuration of the knot enabled consistency in results between operators. With standard arthroscopic knots, differences in operator technique may influence the reproducibility of the repair. Furthermore, the SDs of the Proknot configurations were less than those of the surgeon-tied knots, suggesting that Proknot may be a more reproducible knot.

A recent study by Hanypsiak et al. concluded that the quality of arthroscopically tied knots was inconsistent even among the most experienced arthroscopists. They stated that surgeons were unable to tie 5 consecutive knots consistently, and neither the number of cases performed per year nor years of experience correlated with increased knot reproducibility. Our data suggest that as a more reproducible knot construct, Proknot may be beneficial to all arthroscopic surgeons, independent of their experience.

Limitations

There are limitations to our study. This study was performed in a laboratory setting, and not all in vivo variables were replicated. Among others, the effects of temperature, synovial fluid, arthroscopic irrigant, and physiologic forces on knot performance were not evaluated. As a result, extrapolation of any of our findings to improved clinical performance should be done with caution. All knots were tied under optimal conditions in a laboratory setting. Many of the intraoperative challenges were not replicated. We did not account for tissue-provided tension, suboptimal cannula trajectory related to soft tissue, and suture abrasion from manipulation with instruments or cannulas. Additionally, Permacord suture was not tested in the arthroscopically tied knot configurations, and the technique used to measure knot volume has not been validated in the orthopaedic literature.

Conclusions

Compared with other commonly tied arthroscopic knots using no. 2 high-strength suture, the pretied knot with doubled no. 1 high-tensile-strength suture tied with 1, 2, or 3 RHAPs results in a statistically significantly improved strength. The pretied knot has an equivalent cyclic loop elongation and lower ultimate loop elongation with all RHAP configurations. The pretied knot with 2 or 3 RHAPs has a significantly higher ultimate strength than all combinations of arthroscopic knots excluding one. The pretied knot with 1, 2, or 3 RHAPs has significantly less knot volume than all other knots tested and offers a more reproducible knot.

References


