Arthroscopic Knots: Determining the Optimal Balance of Loop Security and Knot Security


Purpose: The purpose of this study was to determine the optimal knot configuration that maximized both knot and loop security when tied with 2 different types of nonabsorbable, braided suture. Type of Study: In vitro biomechanical study. Methods: Six commonly used arthroscopic sliding knots (Duncan loop, Nicky’s knot, Tennessee slider, Roeder knot, SMC knot, Weston knot) with and without a series of 3 reversing half-hitches on alternating posts (RHAPs) as well as a static surgeon’s knot were tied. Two different nonabsorbable, braided sutures were used, and a total of 7 knots were tied for each possible combination of knots and sutures, for a total of 182 knots. Each knot was tied around a 30-mm circumference post to assure a consistent loop circumference of 30 mm before “locking” the complex sliding knots by tensioning the wrapping limb of the suture. Each loop was mounted on a Material Testing System machine, and its circumference was measured at a 5-N preload to assess each knot’s ability to maintain a tight suture loop without slippage (loop security). Knot security was measured as the maximum force to failure at 3 mm of crosshead displacement or suture breakage during single-pull load testing. Results: The surgeon’s knot provided the highest force to failure and the tightest loop circumference whether tied with No. 2 Ethibond (Ethicon, Somerville, NJ) or No. 2 Fiberwire (Arthrex, Naples, FL) suture. Among the sliding knots, the Roeder knot with 3 RHAPs showed the best balance of loop security and knot security when tied with No. 2 Ethibond or No. 2 Fiberwire. Sliding knots tied without RHAPs showed low force to failure and loose suture loops whether tied with Ethibond or Fiberwire. The addition of 3 RHAPs improved knot security and, in most cases, loop security of all the sliding knots. When tying a static surgeon’s knot or a sliding knot with RHAPs, using No. 2 Fiberwire increased the force to failure over comparable knots tied with No. 2 Ethibond. All knots failed by a combination of knot slippage and suture stretch. When using No. 2 Ethibond, securing most sliding knots with 3 RHAPs or tying a surgeon’s knot changed the failure mechanism from knot slippage to suture stretch, suggesting that the maximum knot holding capacity of No. 2 Ethibond had been achieved when tying these knot configurations. However, even at failure forces twice that achieved with No. 2 Ethibond, suture slippage continued to occur with sliding knots with 3 RHAPs using No. 2 Fiberwire. This indicates that the maximum knot holding capacity of No. 2 Fiberwire had not been achieved, and that further knot configurations should be tested. Conclusions: (1) A static surgeon’s knot provides the best balance of loop security and knot security within the knot configurations tested in this study. (2) A sliding knot without RHAPs has both poor loop security and knot security and should not be tied. (3) The addition of 3 RHAPs improves knot security of all sliding knots tested and improves loop security of most of the sliding knots tested. (4) The addition of 3 RHAPs improves the knot security of all sliding knots to adequately resist predicted in vivo loads. (5) The Roeder knot with 3 RHAPs provides the best balance of loop security and knot security within the sliding knot configurations tested in this study regardless of suture type. (6) Tying a surgeon’s knot or a sliding knot with 3 RHAPs using No. 2 Fiberwire increases knot security over the same knot tied with No. 2 Ethibond. Clinical Relevance: This study identifies the static and sliding configurations of commonly used arthroscopic knots in order to aid the surgeon in choosing the most biomechanically effective knot for use in arthroscopic surgery. Key Words: Arthroscopy—Knots—Suture—Biomechanical testing—Loop—Security.
During arthroscopic surgery, the arthroscopist is commonly required to tie an arthroscopic knot to obtain secure tissue fixation. Unfortunately, the arthroscopic surgeon is bombarded by an endless number of combinations of knots (sliding vs. static, simple vs. complex), and suture types (monofilament vs. braided) to achieve this goal. In many cases, surgeon preference is based on empirical data rather than vigorous scientific investigation.

For a knot to be effective, it must possess the attributes of both knot security and loop security. Knot security is defined as the effectiveness of the knot at resisting slippage when load is applied and depends on 3 factors: friction; internal interference; and slack between throws. Loop security is the ability to maintain a tight suture loop as a knot is tied. Thus, any tied knot can have good knot security but poor loop security (a loose suture loop), and therefore be ineffective in approximating the tissue edges to be repaired.

Although previous studies have evaluated knot security, no study has simultaneously measured both knot security and loop security of the various combinations of knots; therefore, the knot that provides the best balance of both attributes is unclear. The purpose of our study was to compare the knot security and loop security of various combinations of commonly used arthroscopic knots tied with 2 different types of nonabsorbable, braided suture. Our hypothesis was that 1 or 2 knots would be clearly superior to the others for the optimal balance of knot security and loop security.

METHODS

Knot Configurations and Suture Types

Six commonly used complex sliding arthroscopic knots were used in this study: the Duncan loop, Nicky’s knot, Tennessee slider, Roeder knot, SMC knot, and Weston knot (Fig 1A-F). A second set of knots was tied with the same 6 sliding knots as base knots secured by a series of 3 reversing half-hitches on alternating posts (RHAPs). Reversing the half-hitches and alternating the posts was performed by alternately tensioning the wrapping limbs with consecutive throws as previously described. In addition, a “surgeon’s” knot was also tied. This comprised a stack of 3 half-hitches (base knot) followed by 3 consecutive half-hitches on alternating posts to represent a standard static knot (Fig 2). This combination of 3 RHAPs has previously been suggested to secure a base knot by converting its failure mode from suture slippage to suture breakage. Thus, a total of 13 different knots were tested.

Two types of braided nonabsorbable suture were used in this study. We chose No. 2 Ethibond (Ethicon, Somerville, NJ) because it is the most commonly used suture in arthroscopic surgery, particularly in procedures about the shoulder. In addition, we tested No. 2 Fiberwire (Arthrex, Naples, FL), a recently introduced braided, nonabsorbable, polyblend suture with reported strength characteristics that are superior to those of No. 2 Ethibond (unpublished data, Arthrex).

Each knot was tied using each of the sutures. Thus, 26 combinations of knot configurations and suture
types were tied. Seven knots were tied for each combination, for a total of 182 knots.

**Knot Tying and Testing Procedure**

All knots were tied by a senior arthroscopic surgeon (S.S.B.) familiar with arthroscopic knot tying. All knots were tied over a plastic post to create a 30-mm suture loop, replicating the suture loop created during arthroscopic rotator cuff repair. As is common clinical practice for complex sliding knots (except the Duncan loop), the knot was “flipped” by tensioning the wrapping limb to lock the knot in place and prevent the knot from slipping backwards. Because the Duncan loop is a pure sliding knot, locking the knot by “flipping” it is not possible. However, the wrapping limbs around the post were tensioned securely to discourage knot slippage.

To optimize the quality of knots and remove any potential bias from the process of knot tying, all knots were hand tied without instruments or cannulas to minimize suture abrasion (abrasion from the knot pusher or cannula) and physical obstructions. During knot tying, care was taken to ensure optimal knot and loop security by removing twists, eliminating slack between throws, and tensioning the 2 suture limbs.1,2

After each knot was tied, the knotted suture loop was removed from the plastic post for biomechanical testing.

A servohydraulic materials testing system (MTS model 858; Bionix, Eden Prairie, MN) was used to test the knot and loop security of each combination of knots and suture types. Two parallel rods were mounted on the actuator and base of the MTS, and each suture loop was placed around the rods so that the knot was positioned between the rods and did not contact either rod (Fig 3). A 5-N preload was then applied. As a measure of loop security, the cross-head distance was then measured, and the circumference of the loop calculated according to the formula displayed in Fig 4.

**Loop and Knot Security**

![Figure 2](image1.png)

*Figure 2.* Static “surgeon’s” knot configuration.

![Figure 3](image2.png)

*Figure 3.* The MTS machine with parallel rods attached to the actuators and the suture loop mounted. Note the position of the knot relative to the rods.

![Figure 4](image3.png)

*Figure 4.* Cross-head displacement was measured at 5 N of preload and the loop circumference calculated according to the following formula:

\[
\text{loop circumference} = 2 \times \text{cross-head displacement} + 4 \times \text{rod radius} + \text{rod circumference}
\]
The suture loops were loaded to failure at a cross-head speed of 1 mm/s, and force and displacement data were recorded every 50 milliseconds. Maximum force to failure was recorded at a cross-head displacement of 3 mm or at suture breakage. The mode of failure was also recorded.

To estimate the amount of knot slippage versus suture elongation (stretch) that occurred during knot testing, a 30-mm unknotted length of each suture was similarly tested between 2 clamps loaded on the MTS machine. Five lengths of suture were tested for each suture type until suture breakage. The amount of elongation and maximum load at failure were recorded.

**Rationale For Experimental Design**

The static surgeon’s knot and the 6 sliding knot configurations were chosen by the senior surgeon (S.S.B.) because they were, in his experience, the most commonly used by instructors and registrants at the many hands-on cadaver courses in which he was involved. A 5-N preload was selected to remove slack from the system at a load well below those seen clinically in the shoulder. Failure was chosen as 3 mm of elongation, because loop elongation of 3 mm or more is generally accepted in the literature as indicative of clinical failure. That is, if a suture holding soft tissue to bone elongates enough to allow the tissue to displace 3 mm from its original position, then fixation has been lost.

Furthermore, we chose a 30-mm loop as a representative size for a loop of suture that attaches soft tissue to bone. By tying the suture tightly around a plastic post with a 30-mm circumference, we were able to create a loop with optimal loop security initially, and we could then see to what degree it maintained its loop security under load.

**Statistical Methods**

Statistical comparisons of load to failure and loop circumference were evaluated using analysis of variance (ANOVA) with a post-hoc Fisher protected least significant difference (PLSD) test; \( P < .05 \) was considered to be statistically significant.

**RESULTS**

**General Results**

Summaries of the force to failure of each of the sliding knots and the sliding knots secured with a series of RHAPs are shown in Figs 5 and 6, respectively. The surgeon’s knot is included in each figure as...
a reference. In all cases, no knots failed by suture breakage, suggesting that all knots failed by a combination of knot slippage and suture elongation.

Summaries of the loop circumference of each of the sliding knots and the sliding knots secured with a series of RHAPs are summarized in Figs 7 and 8, respectively. The surgeon’s knot is included in each figure as a reference. It is important to remember when interpreting these data that because each knot was tied around a 30-mm circumferential post, a loop circumference of 30 mm represents optimal loop security.

Specific Comparisons

Which of the sliding knots (without RHAPs) provides the highest force to failure? When tied with No. 2 Ethibond suture (68.5 ± 3.3 N) or No. 2 Fiberwire suture (74.1 ± 8.8 N), the Weston knot provided the highest load to failure when compared with the other sliding knots ($P < .0001$) (Fig 5). However, the maximum force of the surgeon’s knot was significantly higher than the Weston knot when tied with either Ethibond (102.8 ± 11.5 N) or Fiberwire suture (197.8 ± 37.4 N) ($P < .0001$) (Fig 5).

Which of the sliding knots with 3 RHAPs provides the highest force to failure? When the sliding knots were tied with 3 RHAPs using No. 2 Ethibond suture, the Weston RHAP (100.8 ± 4.1 N), Roeder RHAP (99.5 ± 9.7 N), and SMC RHAP (96.4 ± 15.4 N) provided the highest force to failure (Fig 6). These forces were not significantly different from the force to failure of the surgeon’s knot (102.8 ± 11.5 N; $P > .42$) tied with No. 2 Ethibond suture.

When the sliding knots were tied with 3 RHAPs using No. 2 Fiberwire suture, the Weston RHAP (192.4 ± 32.2 N) provided the highest force to failure (Fig 6). This force was not significantly different from the force to failure of the surgeon’s knot (197.8 ± 37.4 N; $P = .50$).

Does securing a sliding knot with 3 RHAPs improve the force to failure? In all cases, tying with either No. 2 Ethibond or No. 2 Fiberwire suture, the addition of 3 RHAPs after a base sliding knot significantly improved the force to failure (all $P \leq .0001$; compare Figs 5 and 6). When tying with No. 2 Ethibond suture, the mean increase in force to failure by adding 3 RHAPs was 61.5 N (range, 31.7 to 79.1 N) or an increase of 519.6% (range, 46.3% to 1689.5%).
When tying with No. 2 Fiberwire suture, the mean increase in force to failure by adding 3 RHAPs was 105.6 N (range, 77.8 to 122.8 N) or an increase of 559.3% (range, 307.5% to 1085.5%).

Does suture type alter the force to failure of comparable knots? With sliding knots tied without RHAPs, the force to failure was similar to when knots were tied with No. 2 Ethibond or No. 2 Fiberwire suture ($P = 0.18$) (Fig 5). However, with sliding knots tied with 3 RHAPs, all knots tied with No. 2 Fiberwire showed significantly higher force to failure ($P < 0.01$) than knots tied with No. 2 Ethibond except for the SMC RHAP knot (103.1 ± 18.6 N v 96.4 ± 15.4 N, respectively; $P = .403$) (Fig 6). The mean increase of the other 5 sliding knots in force to failure was 57.4 N (range, 20.4 to 92.2 N) or a mean increase of 68.6% (range, 24.4% to 92.0%).

Tying with No. 2 Fiberwire increased the force to failure of the surgeon’s knot by 92% when compared with a surgeon’s knot tied with No. 2 Ethibond (197.8 ± 37.4 v 102.8 ± 11.5 N; $P < .0001$).

Which of the locked sliding knots provides the smallest loop circumference (best loop security)? Of the sliding knots tied with No. 2 Ethibond suture, the Duncan loop, Roeder knot, Weston knot, and Tennessee slider all provided similar loop circumferences at 5 N of preload ($P > .08$) (Fig 7). However, these knots showed very large loops (range, 32.50 to 33.81 mm), which approached our criteria for failure (3 mm of knot slippage) even before any load (other than preload) was applied. Also, the loop circumferences associated with these knots were significantly larger than the loop circumference of the surgeon’s knot (30.51 ± 0.17 mm; $P < .009$).

When tied with No. 2 Fiberwire suture, the Duncan loop provided the smallest loop circumference (30.71 ± 0.36 mm) of all the sliding knots under 5-N preload. It was not significantly different than the surgeon’s knot tied with No. 2 Fiberwire (30.46 ± 0.25 mm; $P = .74$; Fig 7).

Which of the sliding knots tied with 3 RHAPs provides the smallest loop circumference (best loop security)? When tied with No. 2 Ethibond suture, the Roeder RHAP (30.66 ± 0.42 mm), Duncan RHAP (31.23 ± 0.79 mm), and Nicky’s RHAP (31.63 ± 0.20 mm) provided the smallest loop circumferences and were not significantly different from the surgeon’s knot (30.51 ± 0.17 mm; $P > .14$; Fig 8).

Similarly, when tied with No. 2 Fiberwire, the Roeder RHAP (30.70 ± 0.46 mm), Duncan RHAP
(31.24 ± .74 mm), and Nicky’s RHAP (31.30 ± 0.43 mm) provided the smallest loop circumferences and were not significantly different from the surgeon’s knot (30.46 ± 0.25 mm; P < .26; Fig 8).

Does securing a sliding knot with 3 RHAPs decrease the loop circumference (improve loop security)? With knots tied with No. 2 Ethibond suture, the addition of 3 RHAPs decreased the loop circumference of the Nicky’s knot (37.29 ± 4.16 mm v 31.63 ± 0.20 mm; P < .0001), Roeder knot (32.59 ± 0.59 mm v 30.66 ± 0.42 mm; P = .011), the SMC knot (38.19 ± 3.62 mm v 35.58 ± 2.16 mm; P = .007), and the Tennessee slider (33.81 ± 0.66 mm v 32.20 ± 0.42 mm; P = .033; compare Figs 7 and 8). No significant difference was found in the Duncan loop (P = .09) or the Weston knot (P = .266) when tied with or without 3 RHAPs.

When tying knots with No. 2 Fiberwire, the addition of 3 RHAPs decreased the loop circumference of the Nicky’s knot (34.19 ± 2.44 mm v 31.30 ± 0.43 mm; P = .0002) and the Roeder knot (33.29 ± 1.01 mm v 30.70 ± 0.46 mm; P = .0007; compare Figs 7 and 8). No significant difference was found in the other knot configurations when tied with No. 2 Fiberwire (P > .157).

Does suture type alter the loop circumference (loop security) of comparable knots? When tying sliding knots without RHAPs, the Duncan loop (30.71 ± 0.36 mm v 32.50 ± 1.25 mm; P = .018), Nicky’s knot (34.19 ± 0.19 mm v 37.29 ± 4.16 mm; P < .0001), and SMC knot (35.51 ± 1.28 mm v 38.19 ± 3.62 mm; P = .0005) showed loop circumferences that were significantly smaller when tied with No. 2 Fiberwire suture than when tied with No. 2 Ethibond suture (Fig 7). No other significant differences were seen for the other sliding knots (P > .34).

When sliding knots were tied with RHAPs, no significant difference was seen in the loop circumferences obtained when tying with No. 2 Ethibond or No. 2 Fiberwire suture (Fig 8; all P > .13).

Which knots provide the best balance of knot security and loop security? When evaluating all the knots, the knot that provided the best knot security and loop security in all cases, whether tying with No. 2 Ethibond or No. 2 Fiberwire, was the surgeon’s knot. However, if one wishes to tie a sliding rather than a

**Figure 8.** Loop circumference of locked sliding knots secured with 3 RHAPs and the surgeon’s knot using No. 2 Ethibond (white boxes) and No. 2 Fiberwire (black boxes). Tenn, Tennessee slider.
When evaluating the sliding knots without RHAPs tied with No. 2 Ethibond, the Weston knot provided the best knot security, and the Duncan loop, Roeder knot, and Weston knot provided comparable loop security. However, despite being the 3 best knots of the group, the Duncan loop, Roeder knot, and Weston knot had such poor loop security (all loop circumferences $>32.5\,\text{mm}$), that none of these knots are recommended to be tied without RHAPs.

Alternatively, when evaluating sliding knots without RHAPs tied with No. 2 Fiberwire, the Duncan loop provided the best loop security ($30.71\pm36\,\text{mm}$), and the Weston knot provided the best knot security ($74.10\pm8.80\,\text{N}$). However, even though the Duncan loop tied with No. 2 Fiberwire had excellent loop security, it had poor knot security ($24.49\pm5.71\,\text{N}$). Similarly, despite having excellent knot security, the Weston knot had poor loop security ($32.31\pm0.61\,\text{mm}$). Thus, with No. 2 Fiberwire, none of the sliding knots without RHAPs is recommended.

With sliding knots with RHAPs using No. 2 Ethibond, the Roeder RHAP ($30.66\pm0.42\,\text{mm}$), Duncan RHAP ($31.23\pm0.79\,\text{mm}$), and Nicky’s RHAP ($31.63\pm0.20\,\text{mm}$) knots had the best loop security, while the Weston RHAP ($100.17\pm4.12\,\text{N}$), Roeder RHAP ($99.51\pm9.7\,\text{N}$), and SMC RHAP ($96.39\pm15.42\,\text{N}$) knots had the best knot security. Thus, the Roeder RHAP knot provided the best balance of both loop security and knot security when tying with No. 2 Ethibond.

When tying sliding knots with RHAPs using No. 2 Fiberwire, the Roeder RHAP ($30.70\pm0.46\,\text{mm}$), Duncan RHAP ($31.24\pm0.74\,\text{mm}$), and Nicky’s RHAP ($31.30\pm0.43\,\text{mm}$) knots had the best loop security, and the Weston RHAP knot ($192.36\pm32.22\,\text{N}$) had the best knot security. However, when tied with No. 2 Fiberwire the Weston RHAP knot had poor loop security ($31.95\pm0.60\,\text{mm}$) and thus could not be recommended. In contrast, the Roeder RHAP ($157.24\pm24.69\,\text{N}$) provided significantly ($P = .0012$) higher knot security than the Duncan RHAP ($124.22\pm23.15\,\text{N}$) or the Nicky RHAP ($130.86\pm16.12\,\text{N}$) and thus provided a better balance between knot security and loop security.

Therefore, with either No. 2 Fiberwire or No. 2 Ethibond, the Roeder knot tied with 3 RHAPs provides the best balance of loop and knot security of all the sliding knots tested. In addition, tying the Roeder RHAP with No. 2 Fiberwire provides a significantly higher force to failure than tying with No. 2 Ethibond ($157.24\pm24.69\,\text{N}$ vs $99.51\pm9.66\,\text{N}$; $P < .0001$). No significant difference was found in the loop circumference of the Roeder RHAP when tied with either suture type ($P = .96$).

What was the mode of failure for each knot and suture type? To estimate the amount of knot slippage versus suture stretch that contributed to the failure of each knot, 30 mm unknotted lengths of each suture were tested in the same fashion as the knotted loops, until suture breakage. Each load-elongation curve showed a straight line before failure, confirming that no suture slippage occurred at the suture-clamp interface before failure and validating the calculation of the slope of each curve.

Results showed that No. 2 Ethibond elongated a mean of $8.60\,\text{mm}$ ($28.7\%$) at a maximum load of $128\pm3.8\,\text{N}$ at failure, and No. 2 Fiberwire elongated a mean of $3.12\,\text{mm}$ ($10.4\%$) at a maximum load of $250.0\pm17.8\,\text{N}$. This difference was statistically significant ($P < .00001$).

To estimate the amount of suture stretch versus knot slippage that contributed to the failure of each suture loop, it should be remembered that no knots failed by suture breakage and thus failure occurred by a combination of knot slippage and suture elongation. As an estimate of suture elongation, the amount of elongation...
tion that would occur at the maximum load of failure for each knot was calculated using the mean slope of the suture load-elongation curve. Because we defined clinical failure as 3 mm of cross-head displacement, the suture loop circumference theoretically must increase 6 mm to achieve this displacement. Estimated knot slippage was therefore calculated as the residual amount of suture loop enlargement that was not accounted for by elongation (knot slippage [in millimeters]/suture elongation [in millimeters]).

The estimated amount of suture elongation and knot slippage for each knot is summarized in Table 2. Some knots had estimated elongations greater than 6 mm (and therefore negative calculated knot slippages), because we tested a loop during knot testing and a length of suture during suture testing. As the suture winds around each metal rod of the MTS, local stress risers account for the difference between measured and estimated elongations.

Results showed that when tying with No. 2 Ethibond or No. 2 Fiberwire, the major mechanism of failure for the sliding knots tied without RHAPs was knot slippage. However, when similar sliding knots were secured with 3 RHAPs and tied with No. 2 Ethibond, the amount of knot slippage significantly decreased ($P < .0003$), with a concomitant increase in the amount of suture elongation ($P < 0.005$). This suggested that adding 3 RHAPs altered the failure mechanism from knot slippage to suture elongation when tied with No. 2 Ethibond.

If the testing continued beyond 3 mm of cross-head displacement, suture breakage would probably occur. However, we concluded each test at 3 mm of displacement and therefore did not reach the breaking point of the suture. In essence, by securing a sliding knot with 3 RHAPs, particularly the Tennessee slider RHAP, SMC RHAP, Roeder RHAP, and Weston RHAP, we made the weak link the suture. Thus, these knot con-

### Table 2. Estimated Failure Mechanisms by Suture Elongation or Knot Slippage of Arthroscopic Knots Tied With No. 2 Ethibond Or No. 2 Fiberwire

<table>
<thead>
<tr>
<th>Knot Configuration</th>
<th>Failure Load (N)</th>
<th>Estimated Elongation (mm)</th>
<th>Estimated Elongation (%)</th>
<th>Estimated Slippage (mm)</th>
<th>Estimated Slippage (%)</th>
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<tbody>
<tr>
<td>Ethibond Duncan</td>
<td>19.7</td>
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<td>16.5</td>
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<td>5.2</td>
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<td>40.0</td>
<td>3.6</td>
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<tr>
<td>Surgeon’s</td>
<td>197.8</td>
<td>2.5</td>
<td>41.1</td>
<td>3.5</td>
<td>58.9</td>
</tr>
</tbody>
</table>

Abbreviations: Tenn, Tennessee slider; RHAP, reversing half-hitches on alternating posts.
figurations have reached the maximum knot holding capacity of No. 2 Ethibond suture. This phenomenon was also shown in the surgeon’s knot tied with No. 2 Ethibond suture.

In contrast, sliding knots with RHAPs tied with No. 2 Fiberwire had significantly different results. Because the estimated amount of elongation from No. 2 Fiberwire suture was significantly less than the estimated amount of elongation from No. 2 Ethibond suture, the proportion of failure secondary to knot slippage was higher in the No. 2 Fiberwire suture than for knots similarly tied with No. 2 Ethibond (P < .00004). This is despite the fact that knots tied with RHAPs using No. 2 Fiberwire had significantly higher failure forces (5 of 6 knots; mean increase: 68.6%; range, 24.4% to 92.0%; P < .01) than similar knots tied with No. 2 Ethibond.

Although at first it may appear that knots tied with RHAPs using No. 2 Fiberwire are subject to more knot slippage than those tied with No. 2 Ethibond, these findings are not directly comparable because the maximum failure forces of No. 2 Fiberwire are much higher than those of No. 2 Ethibond, and No. 2 Ethibond stretches much more than No. 2 Fiberwire. As an example, at 100 N of load, the Weston RHAP tied with No. 2 Ethibond would have shown clinical failure with a 6-mm elongation of the suture loop (3 mm of cross-head displacement or 3 mm of displacement of the rotator cuff from the bone). In contrast, a Weston RHAP tied with No. 2 Fiberwire at 100 N of load would have only increased its suture loop by 1.6 mm (0.8 mm of cross-head displacement or 0.8 mm of displacement of the rotator cuff from the bone), clearly a more advantageous clinical scenario. Furthermore, the fact that the No. 2 Fiberwire suture continues to slip despite the addition of 3 RHAPs, or with a surgeon’s knot, suggests that the knot configuration that maximizes the suture’s knot holding capacity has not been obtained and that the addition of further RHAPs or other knot configurations may further increase the force to failure and eliminate any component of knot slippage.

DISCUSSION

Optimization of both knot security and loop security for any given knot is critical, and recommendations regarding a specific knot should not be made without taking both characteristics under consideration. In this study, the loop security of almost all sliding knots tied without RHAPs (except the Duncan loop tied with No. 2 Fiberwire) was poor. Indeed, at a preload of only 5 N, many of the loop circumferences tied with No. 2 Ethibond were approaching our criteria for knot failure during knot security testing (3 mm of suture slippage). This finding suggests that, clinically, these knots may be tied with loose suture loops, thereby allowing loss of tissue apposition and failure of rotator cuff repair or Bankart repair.

During tying, we noted 2 distinct mechanisms causing expansion of the suture loops. In the Duncan loop, because no mechanism for locking the knot exists, the suture loop expands until the knot tightens to a point where its knot security can resist 5 N of load. We believe that this increased knot security occurs because the wrapping limbs tighten (removal of slack) around the post until the internal interference and friction are high enough to resist the applied load.

In the other sliding knots, although the above mechanism was also suspected to occur to some degree, locking the knot by tensioning the wrapping limb and “flipping” the knot also provided another potential mechanism of enlargement of the suture loop. Although this locking mechanism is particularly useful in preventing the knot from sliding back, locking the knot also causes expansion of the suture loop (Fig 9). This effect was seen in almost every knot that required a flipping maneuver to be locked, as explained in the following paragraphs and illustrations.

One of the authors (K.C.C.) has previously classified sliding knots as either lockable or nonlockable, with lockable knots further divided into proximal-locking and distal-locking knots (Fig 10A-C). For example, the Duncan loop is a nonlocking sliding knot. In the case of the Duncan loop, slippage is prevented by the tight grip of the wrappings around the initial post (Fig 10A). In lockable sliding knots, tensioning the wrapping limb distorts the post limb, resulting in a kink in the post, thereby increasing the internal interference that increases the resistance of the knot from backing off. Clinically, after properly seating the knot at the repair site, the wrapping limb is tensioned, flipping the knot and preventing the knot from backing off. This locking effect is also known as the “one-way ratchet effect” or the “self-locking effect.”

Locking knots have previously been divided into proximal-locking and distal-locking knots (as referenced relative to the surgeon) according to where the wrapping limb deforms the post limb when it is tensioned. That is, a proximal-locking knot deforms in the portion of the knot that is closest to the surgeon (Fig 10B), whereas a distal-locking knot deforms in the part of the knot that is furthest away from the
surgeon (Fig 10C). Proximal-locking knots include the Nicky’s knot, and distal-locking knots include the Weston knot and Roeder knot. With the development of other knot configurations (the SMC knot), we propose that a third group be added, the middle-locking knot. In these knots, the wrapping limb emerges from the central part of the knot and include the SMC knot and the Tennessee slider.

The advantage of the proximal-locking knots over the middle-locking or distal-locking knots is the ease with which the knot can be locked particularly when the tension in the knot loop is high. However, when locking various sliding knots, we also noted that distal-locking knots tended to cause less enlargement of the suture loop than proximal-locking or middle-locking knots. This was shown by a trend toward smaller suture loops in distal-locking knots compared with middle-locking and proximal-locking knots (when combined as a group) when tying sliding knots without RHAPs (32.78 ± 0.42 mm vs 35.45 ± 1.91 mm; \( P = .017 \)) and sliding knots with RHAPs (31.35 ± 0.77 mm vs 32.97 ± 0.76 mm; \( P = .077 \)).

Thus, when tying sliding knots clinically, surgeons must be careful when locking the knot to ensure that a tight suture loop (loop security) is maintained. Clearly, some lockable sliding knots (Roeder RHAP) caused less suture loop enlargement than other lockable sliding knots (SMC RHAP, Tennessee slider RHAP). Thus, this factor must be considered when choosing an arthroscopic knot.

The other attribute important to consider when evaluating arthroscopic knots is knot security. In this study, we chose to measure the maximum force at clinical failure determined by either suture breakage or by cross-head displacement of 3 mm. In all cases, even in knots secured by 3 RHAPs, cross-head displacement of 3 mm occurred before suture breakage, suggesting that the suture loops failed by a combination of knot slippage and suture elongation. We agree with previous authors\textsuperscript{15-26} that 3 mm or more of cross-head displacement constitutes knot failure because loss of meaningful tissue fixation has occurred. Previous studies\textsuperscript{15} have suggested that, when tying with No. 2 Ethibond, if the surgeon secures the base knot with 3 RHAPs, he will convert the mode of knot failure from suture slippage to suture breakage. This hypothesis was indirectly confirmed in our study, in which the mechanism of failure for sliding knots tied with No. 2 Ethibond was converted from knot slippage to suture elongation with the addition of 3 RHAPs. Continuing our loading protocol would have likely resulted in suture breakage.\textsuperscript{26}

In addition, we evaluated knot security using single-pull loads rather than cyclic loads. Single-pull loading...
was performed, because, under cyclic loading conditions, suture failure is unlikely to occur because biologic failure (tendon or bone) occurs more readily.\textsuperscript{30,31} In contrast, under single-pull loads, rotator cuff repair constructs will usually fail by suture failure.\textsuperscript{32} Thus we chose to study knot security under conditions that would preferentially lead to suture failure (single-pull loads). These conditions may be seen clinically during a fall or a sudden reflexive arm movement that would cause a maximal contraction of the repair construct.

The underlying question when evaluating knot security, however, is how much is enough. That is, how strong must the knot be? The senior authors (S.S.B., K.A.A.) have shown that, for a standard 4-cm tear, the load per suture ranges from 37.7 to 60.4 N depending on the number of suture anchors and sutures used in each construct.\textsuperscript{1} With sliding knots without RHAPs, only the Weston knot provided enough knot security to adequately resist a 60.4-N load (No. 2 Ethibond mean force to failure = 68.49 N; No. 2 Fiberwire mean force to failure = 74.10 N), although without a wide margin of safety. Because of the combination of poor loop security and poor knot security, we believe that sliding knots without RHAPs are not adequate for clinical use. In contrast, adding 3 RHAPs significantly increased the force to failure of all knots, whether tied with No. 2 Ethibond or No. 2 Fiberwire, and the failure forces were greater than 60.4 N in all cases (range: 67.64 N to 192.36 N). Therefore, clinically any sliding knot tied with 3 RHAPs is likely secure enough to withstand the predicted in vivo forces. This finding emphasizes the importance of securing all sliding knots with 3 RHAPs. Furthermore, it stresses the importance of loop security (as explained previously) in differentiating the sliding knots tied with RHAPs.

Although all the sliding knots with 3 RHAPs tied with No. 2 Ethibond were strong enough to resist the calculated maximum in vivo load of 60.4 N, some of these knots had a very small safety margin (the Duncan RHAP failed at 67.6 N, and the Nicky’s RHAP at 70.8 N). To determine whether suture type could increase that safety margin for a given knot type, we looked at these same sliding knots tied with No. 2 Fiberwire. When tied with No. 2 Fiberwire, each sliding knot tied with 3 RHAPs (except the SMC RHAP) exhibited a force at failure that was significantly higher than comparable knots tied with No. 2 Ethibond (Table 2).

Although the breaking strength of No. 2 Fiberwire was significantly higher than No. 2 Ethibond in our study (250.0 \( \nu \) 128 N), the fact that none of our knots

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure10.png}
\caption{Classification of sliding knots. (A) Nonlocking sliding knot (Duncan loop). Slippage is discouraged by tensioning the wrapping limb, which tightens the wrappings around the post limb but does not distort the post limb. (B) Proximal-locking sliding knot (Nicky’s knot). Slippage is discouraged by tensioning the wrapping limb, which distorts the post limb in the proximal part of the knot. (C) Distal-locking sliding knot (Weston knot). Slippage is discouraged by tensioning the wrapping limb, which distorts the post in the distal part of the knot.}
\end{figure}
failed by suture breakage suggests that No. 2 Fiberwire may improve knot security through a different mechanism. Because the amount of elongation was significantly less when using No. 2 Fiberwire versus No. 2 Ethibond, it is possible that this characteristic in part contributed to a tighter suture loop under load and subsequent higher forces to failure. In the future, it will be important to conduct cyclic load testing on both suture types to determine how much of this elongation will result in permanent deformation and complete loss of tissue apposition.

The fact that, for a given knot type, the force to failure for No. 2 Fiberwire is significantly greater than that for No. 2 Ethibond indicates that material properties of suture can increase knot holding capacity, thereby increasing the margin of safety in clinical practice. Interestingly, even when tying a surgeon’s knot with No. 2 Fiberwire, knot failure was secondary to both knot slippage and suture stretch at 197.8 N of force. This suggests that when tying the knots evaluated in this study with No. 2 Fiberwire, the knots were still the “weak link” in the suture loop, because they continued to slip. Thus, the maximal knot holding capacity of this suture had not been achieved. Although further knot configurations should be tested, we would estimate that the force to failure would be approximately 250 N (maximum force at suture breakage). Although one would not expect to see such a large force in the postoperative rotator cuff repair construct, achieving the maximum knot holding capacity of the suture is desirable to eliminate any component of knot slippage.

Finally, it is important to consider that, among all the knots tested, the surgeon’s knot provided the best loop security and knot security in all cases. Although arguably more difficult to tie, static nonsliding knots, such as the surgeon’s knot, can be tied as well arthroscopically as by hand by using instruments such as a double-diameter knot pusher (Surgeon’s Sixth Finger, Arthrex). In contrast to a static surgeon’s knot, sliding knots cannot be used in situations in which the suture cannot easily slide through the tissue and anchor. However, sliding knots are advantageous because, after they are properly formed extracorporeally, they can be slid down the post limb without allowing the loop to loosen.

Clinically, sliding knots can potentially damage the soft tissues such as the rotator cuff tendon as the suture slides through the tissue, or the suture may abrade and weaken as it slides against the eyelet of the anchor (especially metal anchors). Thus, other factors (suture abrasion, tissue damage, ease of knot tying, bulk of knot) in addition to loop security and knot security should be considered when finally determining which knot to tie.

In conclusion, this study shows the following important points about arthroscopic knots:

A static surgeon’s knot provides the best balance of loop security and knot security within the knot configurations tested in this study.
A sliding knot without RHAPs has both poor loop security and knot security and should not be tied.
The addition of 3 RHAPs improves knot security of all sliding knots tested and improves loop security of most of the sliding knots tested.
The addition of 3 RHAPs improved the knot security of all sliding knots to adequately resist predicted in vivo loads.
The Roeder knot with 3 RHAPs provides the best balance of loop security and knot security within the sliding knot configurations tested in this study, regardless of suture type.

Tying a surgeon’s knot or a sliding knot with RHAPS using No. 2 Fiberwire increases knot security in comparison to the same knot tied with No. 2 Ethibond.

REFERENCES

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