

## Comparing the Influence of Different Overhand/Underhand Stacking Combinations of Reversing Half-Hitches on Alternating Posts on Arthroscopic Knot Security

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### ABSTRACT

**Introduction.** Previous literature demonstrated the importance of stacking at least three reversing half-hitches on alternating posts (RHAPs) following arthroscopic knot placement. However, RHAPs construction involves looping the suture in either an “overhand” or an “underhand” manner as it relates to the post, which may affect knot security. This study investigated the presently unidentified influence of different stacking combinations of three RHAPs and suture material on arthroscopic knot security.

**Methods.** Four different RHAPs stacking combinations were tied with three different suture materials. Ten knots of each configuration were tied using each suture material, resulting in 120 evaluated knots. A single load-to-failure test was performed. The mode of failure and mean ultimate clinical failure load were recorded.

**Results.** Different overhand/underhand stacking combinations of three RHAPs had a statistically significant effect on arthroscopic knot strength and security; however, all combinations surpassed the minimum ultimate clinical failure threshold. Knots constructed with either Force Fiber<sup>®</sup> or braided fishing line had mean ultimate clinical failure loads of greater than 200 N and most commonly failed due to suture material breakage (100%, 60 - 80% respectively). Conversely, FiberWire<sup>®</sup> demonstrated lower mean ultimate clinical failure loads and had a higher incidence of elongated but intact failure (60 - 90%).

**Conclusion.** Different overhand/underhand stacking combinations of three RHAPs yielded an arthroscopic knot capable of secure tissue fixation. A significant effect was observed for suture materials on the knot strength. This study increases our understanding of suitable RHAPs construction following arthroscopic knot placement that can lead to improving the ultimate clinical failure loads of constructed arthroscopic knots observed between orthopedic surgeons.

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### INTRODUCTION

During arthroscopic surgery, the surgeon commonly is required to tie a sliding arthroscopic knot followed by three reversing half-hitches on alternating posts (RHAPs) to yield a knot capable of secure tissue fixation.<sup>1-5</sup> A half-hitch is created by either sliding the loop suture limb under and over the post suture limb (underhand technique) or by sliding the loop suture limb over and under the post suture limb (overhand technique).<sup>6</sup> Great interest has been generated by the precise tying of the three RHAPs because of its potential impact on knot security.<sup>2-5,7-13</sup>

Chong et al.<sup>7</sup> evaluated the effect of differently stacked RHAPs configurations on knot security and their results validated that when two of the half-hitches of the RHAPs were reversed, the knot had better holding strength. Chan et al.<sup>14</sup> described a technique for switching posts simply by alternating tension on the suture limbs, whereby the knot “flips” and the wrapping limb (or the loop suture limb) effectively becomes the post suture limb. The direction of the loop suture limb as it pertains to the post will determine this configuration. The half-hitch created by overhand configuration when “flipped” formed a “reversed underhand” half-hitch, and similarly the underhand half-hitch configuration when “flipped” formed a “reversed overhand” half-hitch (Figure 1).

Many orthopedic surgeons have been taught throughout their resident training to construct the three RHAPs sequence in an ‘underhand, overhand, underhand’ configuration. However, because of this “flipping” phenomenon,<sup>14</sup> they may proceed without realizing that the final RHAPs sequence is converted to a ‘reversed overhand, overhand, reversed overhand’ configuration when the first and the third underhand half-hitch configurations are “flipped.” The question remains whether this final RHAPs combination will affect arthroscopic knot holding strength.

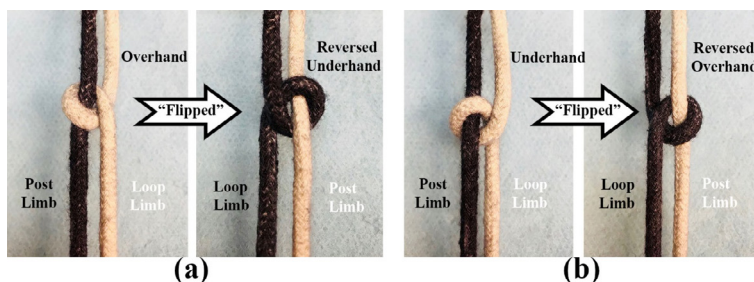


Figure 1. Post suture limb “flips” to loop suture limb with Chan et al.<sup>14</sup> switching post technique; Overhand configuration (first set of pictures) “flipped” to “reversed underhand” (second set of pictures).

Furthermore, suture materials affect the loop and knot security of arthroscopic knots.<sup>7,12,15-18</sup> Force Fiber<sup>®</sup> is made with braided ultrahigh molecular weight polyethylene (UHMWPE) with variations in weave patterns used, whereas FiberWire<sup>®</sup> has a multi-fiber UHMWPE core covered with braided polyester suture material. Overall, these two sutures are made of similar materials, but with varying designs. As a result, different mechanical and handling properties have been reported. To our knowledge, there has not been a study documenting the effect of different overhand/underhand stacking combinations of three RHAPs involving different suture materials on arthroscopic knot security.

The specific aims of this study were to 1) evaluate the effect of different overhand/underhand stacking combinations of three RHAPs on arthroscopic knot strength and integrity, and 2) determine the influence of the suture material upon the loop and knot security.

## METHODS

Four different overhand/underhand stacked RHAPs configurations were tied following advancement of three identical half-hitches stacked on the same post, otherwise known as the Surgeon's knot (Figure 2):

- Configuration 1: Reversed underhand – overhand – reversed underhand
- Configuration 2: Reversed overhand – underhand – reversed overhand
- Configuration 3: Reversed overhand – overhand – reversed overhand
- Configuration 4: Reversed underhand – underhand – reversed underhand

Three types of braided suture materials were included:

- No. 2 Force Fiber® (Stryker, San Jose, CA)
- No. 2 FiberWire® (Arthrex, Naples, FL)
- Braided fishing line (Power Pro Microfilament Braided Line, Irvine, CA)

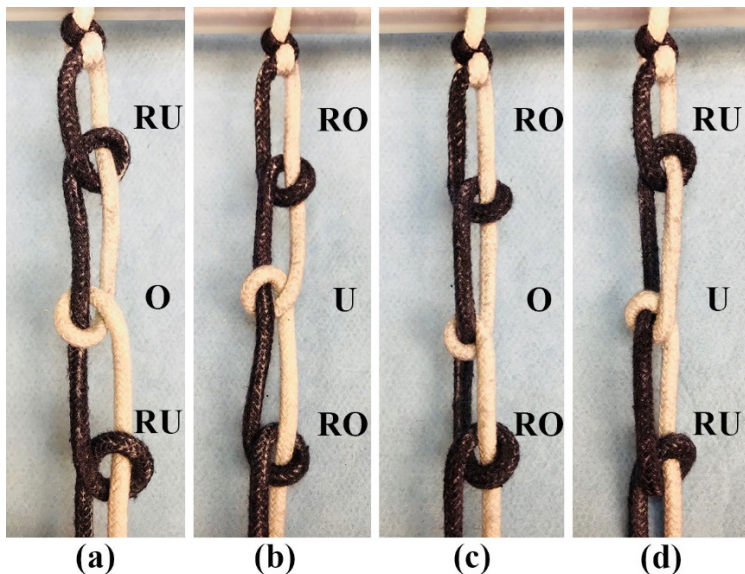


Figure 2. Four RHAPs stack combinations were evaluated: (a) Configuration 1: reversed underhand (RU) - overhand (O) - reversed underhand (RU); (b) Configuration 2: reversed overhand (RO) - underhand (U) - reversed overhand (RO); (c) Configuration 3: reversed overhand (RO) - overhand (O) - reversed overhand (RO); (d) Configuration 4: reversed underhand (RU) - underhand (U) - reversed underhand (RU).

The braided fishing line was chosen based on its similarity to commercially available suture material in terms of line diameter (0.46 mm vs suture: 0.50 mm), manufacturer's tested strength (356 N vs. suture: 228 N), and weaved pattern. Forty-five centimeters (18 inches) of each material was used for constructing all knots. A custom-designed arthroscopic knot-tying apparatus was used for tying knots with a standard knot pusher replicating standard arthroscopic technique in a dry laboratory environment (Figure 3). This apparatus is similar to other published studies.<sup>7,9,11,15,16,19,20</sup> All knot-tying processes began by advancing the Surgeon's knot down to a standardized 30 mm

circumference post to provide a consistent starting circumference for each knot. All knots were tied using standard techniques with a single-hole knot pusher through a cannula in a dry environment using a load cell (Portable Electronic Scale, China) to standardize the strength used to tighten the half-hitches. Each of the half-hitches were tightened manually to at least 45 N (10 lbs) using an over-pointing or past-point technique. After each knot was tied over the post, the knotted suture loop was removed from the post and was trimmed, leaving approximately 6 mm length tags from the most distal end of the knot. Each of the four configurations were tied 10 times using each suture material, resulting in a total of 120 evaluated knots.

A single load-to-failure test was performed with a servohydraulic materials testing system (model 8874; Instron, Norwood, MA) to evaluate the tensile knot strength. The experimental setup and test protocol were similar to those previously described in the literature for consistency.<sup>2,3,7,9,15,16,19-22</sup> The knots were mounted around two 3.9 mm diameter hooks that attached to the actuator and the load cell (Figure 4). Each suture loop was initiated with five preconditioned loading cycles from 6 N to 30 N at 1 Hz to avoid potential errors produced from slack in the loops and stretching of the suture materials. Loops were then pre-loaded to 6 N to provide a well-defined starting point for data collection. The loops were then continuously loaded to failure at an across-head speed of 1.0 mm/sec until complete structure failure occurred or a 10 mm relative crosshead displacement was reached. Load and displacement data were collected at 100 Hz, and the mode of knot failure was recorded. This study defined three modes of knot failure: 1) failure by the suture material, 2) knot loop elongated but remained intact, and 3) knot slippage.

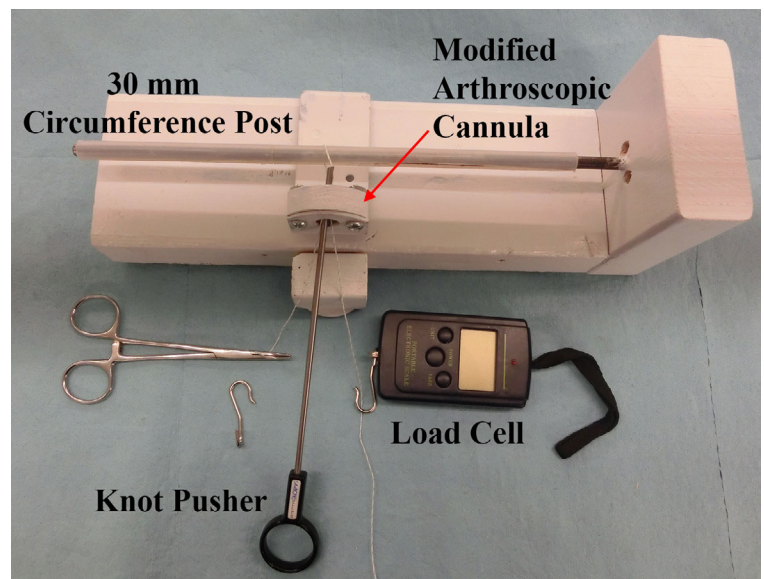


Figure 3. Knot tying setup.

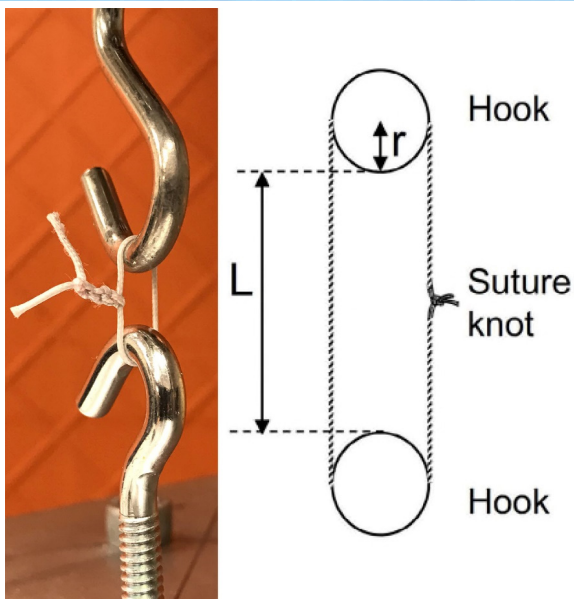


Figure 4. Load-to-failure experimental setup.

“Clinical failure” was defined as knot slippage of 3 mm (cross-head displacement), which is supported by previously performed assessments of arthroscopic suture and knot testing.<sup>2-5,7,15, 16,21-26</sup> The “fail” criteria was defined as (1) the ultimate tensile knot strength at crosshead displacement less than 3 mm with less than 100 N load, as previous studies have determined that 100 N is the estimated minimum required ultimate load per suture during maximum muscle contraction<sup>23,24</sup> and (2) the initial loop circumference at 6 N preload with more than 33 mm (circumference of the standardized post from the knot-tying apparatus: 30 mm). The initial loop circumference of the loop was calculated according to the formula:

$$CL = (2 * L) + (4 * r) + Cr \quad \text{Eqn 1}$$

CL represents loop circumference, L represents crosshead displacement, r represents rod radius, and Cr represents rod circumference.

**Statistical Analysis.** Data retrieved from the load-to-failure tests were analyzed for any differences among test configurations using one-way analysis of variance (ANOVA) with the least significant difference (LSD) multiple comparisons post hoc test method in SPSS software (Version 19.0; SPSS Inc, Chicago, IL) with  $p < 0.05$  denoted as significant. The percentage of each failure mode group was calculated for each configuration and each suture material. These values were used to determine the statistical relevance of the difference in arthroscopic loop and knot security for each configuration.

**RESULTS**

Figure 5 shows the mean ultimate clinical failure load (3 mm cross-head displacement) of the four overhand/underhand stacked RHAPs configurations using different suture materials. Knots tied with either Force Fiber® or the braided fishing line had mean ultimate clinical failure loads of greater than 200 N, whereas knots tied with FiberWire® had lower mean ultimate clinical failure loads when compared to the other two suture materials. Nevertheless, all knots had mean

ultimate clinical failure loads of more than 100 N, the approximate load exerted per suture during maximum muscle contraction.<sup>1,23,24</sup>

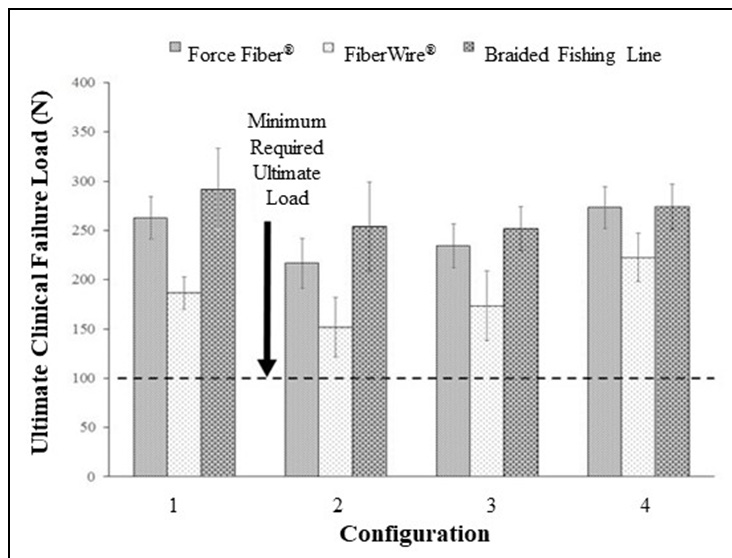


Figure 5. Mean ultimate clinical failure load (3 mm crosshead displacement) of the four overhand/underhand stacked reversing half-hitches on alternating posts configurations for three types of braided suture materials.

There was a statistically significant difference detected between each configuration when either Force Fiber® or FiberWire® was used, except between Configuration 1 and Configuration 4 for Force Fiber®, and between Configuration 1 and Configuration 3 for FiberWire® (Table 1). No significant differences were detected between Configuration 2 and Configuration 3 for all tested suture materials. For braided fishing line, the only statistically significant difference detected was between Configuration 1 and Configuration 2, and between Configuration 1 and Configuration 3 (Table 1).

**Table 1. Statistical analysis for knot tensile strength performance for the three types of suture materials of the four configurations.**

		Force Fiber®	FiberWire®	Braided Fishing Line
Configuration #1	Configuration #2	< 0.001	0.006	0.003
	Configuration #3	0.024	0.296	0.002
	Configuration #4	0.408	0.004	0.156
Configuration #2	Configuration #3	0.158	0.081	0.859
	Configuration #4	< 0.001	< 0.001	0.109
Configuration #3	Configuration #4	0.002	< 0.001	0.075

\*Each table cell value shows the statistical p value with  $p < 0.05$  denoted as significant.

There was a statistically significant difference in knot tensile strength performance when different suture materials were used, except when knots were tied with Configurations 3 and 4 using Force Fiber® and FiberWire® (Table 2). Force Fiber® and braided fishing line had a higher incidence of suture material failure, whereas FiberWire® suture material had a higher incidence of suture loop elongated but intact failure mode (Table 3). It was observed that knots tied with FiberWire® had suture material failure at higher crosshead displacement (Figure 6).

**Table 2. Statistical analysis for knot tensile strength performance for the four configurations of the three types of suture materials.**

		Configuration			
		#1	#2	#3	#4
Force Fiber®	FiberWire®	< 0.001	< 0.001	< 0.001	< 0.001
	Braided Fishing Line	0.021	0.003	0.165	0.934
FiberWire®	Braided Fishing Line	< 0.001	< 0.001	< 0.001	< 0.001

\*Each table cell value shows the statistical p value, with p < 0.05 denoted as significant.

**Table 3. Failure mode test results.**

	Configuration	Suture Material	Elongated but Intact	Knot Slippage
Force Fiber®	#1	100%	0%	0%
	#2	100%	0%	0%
	#3	100%	0%	0%
	#4	100%	0%	0%
FiberWire®	#1	40%	60%	0%
	#2	10%	90%	0%
	#3	10%	70%	20%
	#4	20%	80%	0%
Braided Fishing Line	#1	80%	20%	0%
	#2	60%	40%	0%
	#3	60%	40%	0%
	#4	80%	20%	0%

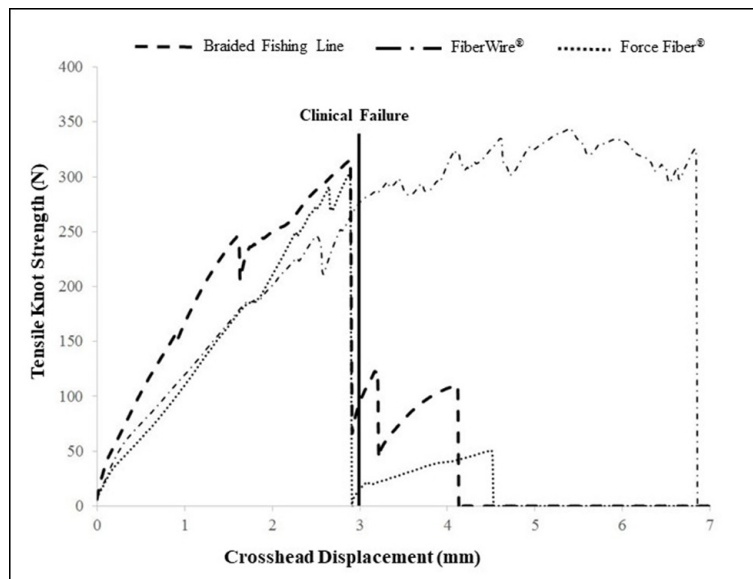


Figure 6. Example of the knot strength and integrity performance for the three types of suture materials.

**DISCUSSION**

Different overhand/underhand stacking combinations of three RHAPs had a statistically significant effect on arthroscopic knot strength and security. Clinically, however, the stacking combinations did not present significant differences among each series that could have clinical implications, as all configurations surpassed the estimated load force exerted during maximum muscle contraction (Figure 5).<sup>23,24</sup> Base knot configuration, suture material, and surgeon experience are each critical factors in optimizing knot strength and security.<sup>4,13,22-29</sup> The findings of this study provided evidence that switching the post suture limb between throws in a series of either overhand or underhand half-hitches is capable of generating a secure knot capable of resisting slippage when a load is applied.

The influence of the suture material upon the loop and knot security was reflected in this study and agreed with previous studies<sup>7,12,15-18</sup> that suture materials containing a core tend to have lower ultimate clinical failure strength and higher prevalence of knot slippage compared to suture materials that are braided with variations in weave patterns. Other studies<sup>7,15,16</sup> have discussed that knot slippage could be affected by the suture surface characteristics and suture construction. Notably, knots tied with FiberWire® had a higher incidence of suture loop elongated but intact failure mode. This potentially could be an advantageous finding, specifically when an individual takes a fall on an outstretched arm or while lifting a heavy object with a jerking motion. In this case, the suture material may become stretched but the knot remains intact preserving its ability to hold the soft tissue rather than total tissue separation.

Moreover, knots tied with the selected 356 N (80 lbs.) tested braided fishing line had similar arthroscopic knot strength and integrity compared to Force Fiber®. Braided fishing line is a suitable and inexpensive suture material for orthopedic surgeons and residents to practice arthroscopic knot tying. Many orthopedic resident programs initially recommend practicing arthroscopic knot tying using large suture or cord, then progressing to standard suture material. Undoubtedly, using large suture or cord for training is beneficial for inexperienced surgeons or residents to become familiar with the basic knowledge of the arthroscopic knot tying; however, it may be disadvantageous when attempting to slide a knot using a material that does not slide freely. Consequently, the trainee may not understand the proper technical aspects of tying and tensioning knots, since it is critical to switch posts when tying RHAPs.<sup>14</sup> This key practice cannot be demonstrated easily or learned with large suture or cord.

Previous studies<sup>7,30,31</sup> demonstrated that over-tensioning on suture limbs easily “flipped” the half-hitch. This is a result of excessively pulling back the knot pusher through the arthroscopic cannula while tying the knot or by turning the suture around the post suture limb, resulting in unintentional tension applied to the loop suture limb. This may even occur when a tightened half-hitch seated on the base knot is slightly over-tensioned (>10 N), causing the half-hitch to flip back.<sup>30</sup>

With large suture or cord, this over-tensioning phenomenon may not be detected or noticeable. Conversely, when training with braided fishing line, critical techniques of arthroscopic knot tying can be followed, demonstrated, and learned. This includes the ability to control the knot pusher, the application of appropriate differential tension on the two free ends of a suture, and mastering the tension sequence of the suture limbs and knot pusher.

This study has certain limitations. First, this biomechanical investigation was performed in a dry laboratory environment at room temperature, whereas a fluid environment with varying temperature could affect the results. Second, knots were tied on a standardized rigid post (30 mm in circumference), which differs from what is performed clinically and cannot account for the variability seen in a clinical setting. Suture loops did not pass through any soft tissue, turn acute angles, risk abrasion on suture anchors, or rub over bony surfaces. Third, only a single load-to-failure test was performed and a leading source of failure in orthopedic repairs has been recognized by cyclic loading.<sup>32-35</sup> Fourth, this study contained only three arthroscopic suture materials and four overhand/underhand stacked RHAPs combinations to secure one simple base knot, the Surgeon's knot. This could limit the generalizability to other suture types or other sliding knot configurations. Fifth, all knots were tied in one day and were tested as a batch, as opposed to immediately being tested after knot construction. This short period of storage could have altered the properties of the knots. Despite the aforementioned limitations, the outcomes of this study provided great value in investigating the unknown influence of different overhand/underhand stacking combinations of three RHAPs involving different suture materials on arthroscopic knot security.

## CONCLUSION

This study indicated that either underhand or overhand stacking combinations of three RHAPs yielded an arthroscopic knot capable of secure tissue fixation. A significant effect was observed for suture materials on the arthroscopic knot strength and security. Caution should be exercised by the surgeon when selecting the suture type for arthroscopic knot construction using standard arthroscopic techniques. This study further aided our understanding of the precision involved with tying three RHAPs, providing clarification that could improve the ultimate clinical failure loads observed between orthopedic surgeons, thereby achieving better clinical outcomes. Our findings also exhibited braided fishing line as a suitable alternate to arthroscopic suture materials for training purposes, providing potential benefit to orthopedic training programs of a resident's ability to follow, learn, and construct a secure arthroscopic knot.

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*Keywords:* arthroscopy, suture techniques, orthopedic surgery, operative procedures