An Original Study

Knot Security, Loop Security, and Elongation of Braided Polyblend Sutures Used for Arthroscopic Knots

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Abstract

In the study described here, we evaluated load to failure and cyclic loading elongation of different braided polyblend sutures under different sliding knot configurations.

Four braided polyblend sutures (FiberWire, Herculine, Orthocord, Ultrabraid) were tied with 5 sliding arthroscopic knots (Static surgeon, Weston, Roeder, Nicky, Tennessee slider) with a series of 3 reversing half-hitches on alternating posts (RHAPs). Each knot was tied around a 30-mm circumference post to ensure a consistent loop circumference. Loop security was measured as load to failure (load at 3-mm cross-head displacement or suture breakage) and loop elongation at a frequency of 1 Hz from 6 N to 30 N for 1000 cycles. Twenty knots were tied for each possible combination of knots and sutures, 10 for load to failure and 10 for cyclic loading test.

For any given knot type, tying with Ultrabraid suture material resulted in maximum performance in the maximum load-to-failure test. Conversely, tying with Orthocord resulted in a significantly lower maximum load to failure, with the exception of the Surgeon knot. The Weston knot with 3 RHAPs using Ultrabraid provided the highest load to failure (mean, 346 N; SD, 24 N). All knots elongated less than 0.45 mm at the 1000th cycle and experienced higher suture slippage at initial cyclic loading (50th cycles). At higher cycles, FiberWire and Orthocord demonstrated less than half of the suture slippage of Herculine and Ultrabraid (5×10^{-5} vs 11×10^{-5} mm/cycle).

Different braided polyblend sutures provide different knot and loop security for a given type of sliding knot. All knots in this study appear to be durable with respect to resistance to loosening under cyclic loading conditions. The Weston knot with 3 RHAPs using Ultrabraid provided the best loop and knot security.

Our study results help further our understanding of the biomechanics of knot and loop security differences for different braided polyblend sutures.

The advancement of arthroscopic soft-tissue repair and knot tying has promoted the need for more manageable and stronger suture materials and has yielded a new generation of polyblend sutures shown to be stronger than previously available materials.[1-5] The ideal suture material should provide adequate strength to hold soft tissue in an anatomically repaired position until healing can occur. It also should be easily and efficiently manipulated by arthroscopic means when securing tissues via knots and secure suture

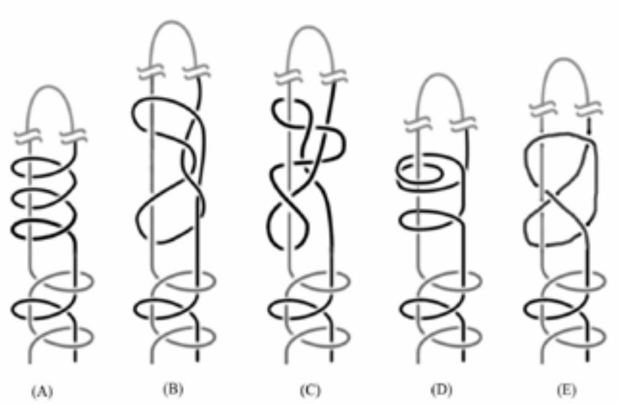

Figure 1. Sliding knot configurations evaluated: (A) static surgeon knot with 3 reversing half-hitches on alternating posts (RHAPs), (B) Weston knot with 3 RHAPs, (C) Roeder knot with 3 RHAPs, (D) Nicky knot with 3 RHAPs, and (E) Tennessee slider knot with 3 RHAPs. Figure 1 provided by Alexander C. M. Chong.

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Am J Orthop. 2010;39(12):569-576.

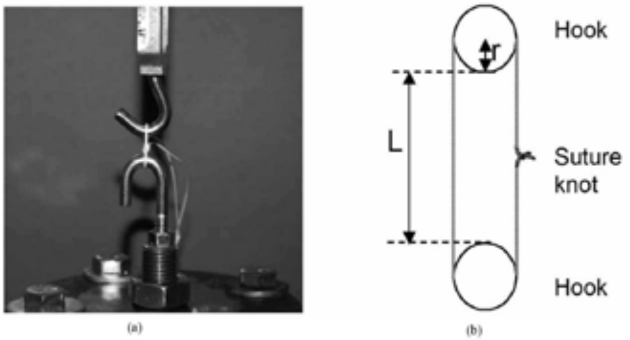

Figure 2. Experimental setup: (A) individual test setup of Material Testing System with 2 hooks attached to actuators and suture loop mounted and (B) schematic representation of cross-head displacement and loop circumference calculated according to formula (see text).

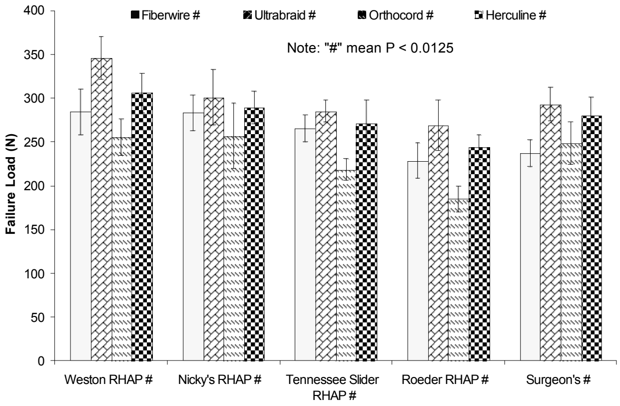

Figure 3. Mean maximum clinical failure load (3 mm displacement) of sliding knots with 3 reversing half-hitches on alternating posts for different braided polyblend sutures.

loops. Loop security is distinguished from knot security by the fact that a suture material with a large elastic elongation (ie, low elastic modulus) can stretch, resulting in a loose loop even if the knot is completely secure. The ideal knot would be easy to tie and reproducible and would not slip or stretch before the tissue has healed. One facet of increased manageability is the ease with which the suture can be passed and secured using a sliding knot. Polyester and polyblend braided sutures have changed arthroscopic soft-tissue repair by providing superior strength compared with traditional suture materials.[1-6] This allows easier knot tying with decreased risk for suture failure and gives excellent loop security for tissue stabilization.[6] Most new-generation sutures have been shown to have similar tensile strengths. FiberWire (Arthrex, Naples, Florida), Herculine (Linvatec, Largo, Florida), Orthocord (DePuy-Mitek, Warsaw, Indiana), and Ultrabraid (Smith & Nephew, Memphis, Tennessee) have attempted to differentiate themselves in the ability to throw arthroscopic sliding knots with more ease and security.[1-5] Herculine and Ultrabraid consist of braided, nonabsorbable polyethylene fibers without a longitudinal core, which is present in FiberWire and Orthocord. FiberWire is made of braided polyethylene and polyester fibers coated with a proprietary coating. Orthocord is composed of dyed absorbable polydioxanone and undyed nonabsorbable polyethylene. Although these sutures are made of similar materials, their designs vary, and they have been reported to have different mechanical or handling properties.[1-5]

The coefficient of friction may be low enough in some of these sutures that sliding knots can be placed with less force to secure the tissue at time of surgery. However, one must worry that the same level of "low friction" may allow these same sutures' sliding knots to loosen when heavily or cyclically loaded. The sliding knots currently in clinical use were developed and tested for use with standard braided polyester suture.[7-9] In this study, we measured how the knots with a series of 3 reversing half-hitches on alternating posts (RHAPs) perform with the newer generation of suture materials. The objective of this study was to evaluate the differences in knot configuration and loop security of different braided polyblend sutures used in arthroscopic

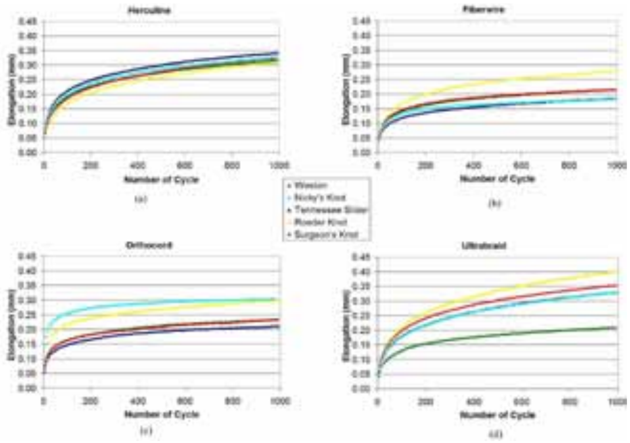

Figure 4. Mean elongation graphs for all knot configurations tested with different braided polyblend sutures. Knots tying with (A) Herculine, (B) FiberWire, (C) Orthocord, and (D) Ultrabraid.

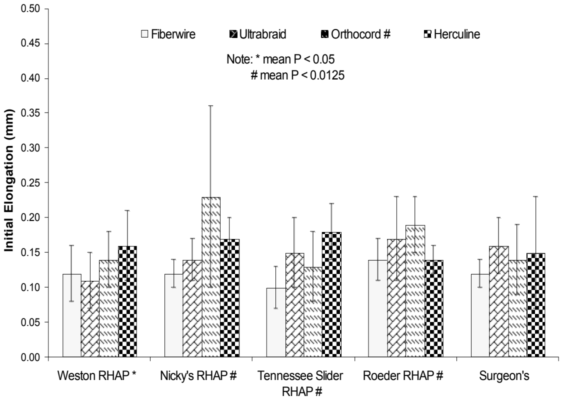

Figure 5. Initial elongation (mean, SD) for each knot configuration.

Table I. Statistical Analysis[a] of Effect of Knot Configuration on Measured Parameters

			P			Overall *P*		
Suture Material	Suture Knot		Load to Failure	Cyclic Load Initial Elongation	Cyclic Load Final Elongation	Load to Failure	Cyclic Load Initial Elongation	Cyclic Load Final Elongation
FiberWire	Weston	Nicky	.000	.749	.129	.000	.190[b]	.000
		Tennessee	.000	.214	.153			
		Roeder	.050	.236	.006			
		Surgeon	.936	.782	.896			
	Nicky	Tennessee	.357	.354	.926			
		Roeder	.000	.135	.000			
		Surgeon	.000	.551	.164			
	Tennessee	Roeder	.002	.018	.000			
		Surgeon	.000	.131	.193			
	Roeder	Surgeon	.042	.361	.004			
Ultrabraid	Weston	Nicky	.000	.085	.001	.000	.055[b]	.000
		Tennessee	.446	.064	.001			
		Roeder	.001	.006	.000			
		Surgeon	.894	.014	.000			
	Nicky	Tennessee	.000	.889	.995			
		Roeder	.003	.258	.044			
		Surgeon	.000	.437	.529			
	Tennessee	Roeder	.006	.320	.044			
		Surgeon	.529	.523	.525			
	Roeder	Surgeon	.001	.719	.158			
Orthocord	Weston	Nicky	.005	.006	.074	.000	.008	.062[b]
		Tennessee	.475	.633	.542			
		Roeder	.154	.130	.099			
		Surgeon	.000	.914	.975			
	Nicky	Tennessee	.032	.002	.018			
		Roeder	.145	.192	.885			
		Surgeon	.000	.005	.079			
	Tennessee	Roeder	.468	.049	.026			
		Surgeon	.000	.712	.522			
	Roeder	Surgeon	.000	.105	.105			
Herculine	Weston	Nicky	.000	.733	.864	.000	.369[b]	.909[b]
		Tennessee	.333	.393	.447			
		Roeder	.067	.276	.869			
		Surgeon	.085	.719	.817			
	Nicky	Tennessee	.000	.606	.555			
		Roeder	.005	.155	.737			
		Surgeon	.000	.485	.951			
	Tennessee	Roeder	.374	.055	.356			
		Surgeon	.009	.227	.596			
	Roeder	Surgeon	.001	.462	.692			

[a] One-way analysis of variance. Means and SDs appear in Figures 3, 5, and 6.

[b] $P>.05$.

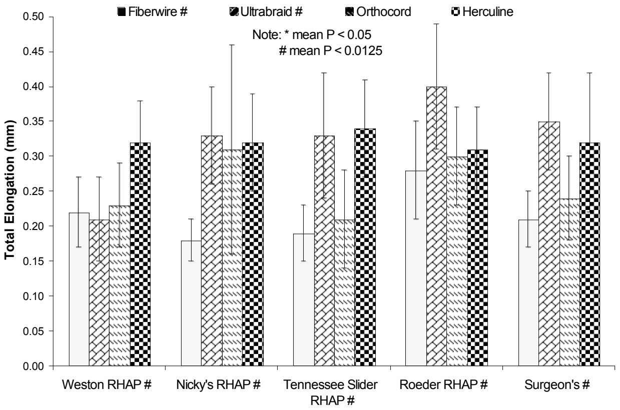

Figure 6. Total elongation (mean, SD) for each knot configuration.

procedures through cyclic loading and load to failure. The null hypothesis for this study was that different braided polyblend sutures would provide the same knot and loop security for the different types of sliding knots in load to failure but may not perform as well under cyclic loading.

MATERIALS AND METHODS

Four types of braided polyblend polyethylene sutures were tested: FiberWire, Herculine, Orthocord, and Ultrabraid. Each suture material was tied with 5 commonly used complex sliding arthroscopic knots with a series of RHAPs: static surgeon knot, Weston knot,[10] Roeder knot,[11] Nicky knot,[12] and Tennessee slider knot[3] (Figure 1). These were chosen based on previous studies[4,8,9,13-16] that showed these types of knots have a higher maximum force to failure when combined with 3 RHAPs.

To eliminate surgeon variation, the study had one orthopedic surgeon, who, familiar with arthroscopic knot tying, tied all the knots. All knots were tied over a standardized 30-mm circumference post that provided a consistent starting circumference for each knot and replicated the suture loop created during arthroscopic rotator cuff repair. All knots were hand-tied without instruments or cannulae to minimize suture abrasion and physical obstruction, using a procedure similar to that of Lo and colleagues.[4] Seven servohydraulic Material Testing System instruments (MTS model 810, and 6 of the MTS model 858 Mini Bionix; Eden Prairie, Minnesota) were used to test the knot and loop security of each combination of knots and suture types. Two roundhooks with a diameter of 3.9 mm were attached to the actuator and the load cell (Figure 2). Loops were preloaded to 6 N to avoid potential errors produced from slack in the loops and stretching of the suture materials and to provide a well-defined starting point for data recording. The distance between the 2 rods was measured (cross-head displacement), and the circumference of the loop was calculated according to the equation $C_L = (2\times L) + (4\times r) + C_r$, where C_L is loop circumference, L is cross-head displacement, r is rod radius, and C_r is rod circumference.

Two types of mechanical testing were performed, and 10 samples of each knot–suture configuration for each mechanical testing were tested for a total of 400 knot–suture combinations. Half the samples were continuously loaded until failure, and the other half were tested with cyclic loading. For load-to-failure testing, each suture loop was loaded in tension from 6 N to failure at a cross-head speed of 1 mm/s. Previous studies have indicated that 3 mm is the point at which tissue apposition is lost.[13,17-19] Therefore, we defined knot slippage to 3 mm (cross-head displacement) as *clinical failure,* which has previously been used as the criterion for evaluation of different knot–suture combinations.[4,7,13,20-22] Testing was initiated with 5 preconditioning loading cycles from 6 N to 30 N at a frequency of 1 Hz. The load then was applied continuously until failure occurred; force and displacement data were collected every 0.01 second. This procedure was repeated for 10 replicates of each combination of knot and suture type.

The cyclic loading test consisted of each suture loop axially loaded from 6 N to 30 N at a frequency of 1 Hz for 1000 cycles. The maximum load of 30 N was chosen based on the procedure described by Elkousy and colleagues,[9] Milia and colleagues,[23] and others.[9,22] Displacement and force data were collected every 5 cycles at maximum load. Elongation of the suture was calculated using the difference between the loop circumference of the 1st cycle and the loop circumference of the final cycle (50th cycle and 1000th cycle). Suture slippage (elongation/number of cycles) was calculated by linear regression. This procedure was repeated to provide 10 replicates for each combination of knot and suture type.

Statistical Analysis

Data retrieved from the load-to-failure and cyclic loading tests were analyzed for any differences among sutures and among knot configurations using general linear model repeated measures of SPSS software (Version 16.0; SPSS, Inc., Chicago, Illinois) with $P<.0125$ denoting significance. Results also were analyzed using 1-way analysis of variance with the least significant difference multiple comparisons post hoc test method with 10 measures per knot–suture configuration. These analyses were used to determine the statistical relevance of the difference between knot failure load, knot slippage for each suture type, and knot slippage for each knot type. Mean and standard deviation were calculated for each configuration.

RESULTS

Across all the suture materials and knot configurations, there was a statistical difference detected among the sutures ($P<.0125$) and among the knot configurations ($P<.0125$) in load-to-failure test, initial cyclic loading test (50th cycles), and final cyclic loading test (1000th cycles).

Table II. Statistical Analysis[a] of Effect of Suture Type on Measured Parameters

Suture Material	Suture Knot		*P*			Overall *P*		
			Load to Failure	Cyclic Load Initial Elongation	Cyclic Load Final Elongation	Load to Failure	Cyclic Load Initial Elongation	Cyclic Load Final Elongation
Weston	FiberWire	Ultrabraid	.000	.541	.776	.000	.035[b]	.001
		Orthocord	.010	.192	.476			
		Herculine	.049	.036	.000			
	Ultrabraid	Orthocord	.000	.059	.321			
		Herculine	.001	.008	.000			
	Orthocord	Herculine	.000	.404	.003			
Nicky	FiberWire	Ultrabraid	.173	.373	.001	.009	.004	.002
		Orthocord	.040	.001	.004			
		Herculine	.648	.102	.001			
	Ultrabraid	Orthocord	.001	.006	.512			
		Herculine	.359	.444	.816			
	Orthocord	Herculine	.014	.039	.671			
Tennessee	FiberWire	Ultrabraid	.018	.043	.000	.000	.007	.000
		Orthocord	.000	.204	.401			
		Herculine	.442	.001	.000			
	Ultrabraid	Orthocord	.000	.423	.000			
		Herculine	.096	.127	.736			
	Orthocord	Herculine	.000	.023	.000			
Roeder	FiberWire	Ultrabraid	.000	.092	.000	.000	.006	.002
		Orthocord	.000	.002	.488			
		Herculine	.102	1.000	.295			
	Ultrabraid	Orthocord	.000	.136	.003			
		Herculine	.009	.092	.007			
	Orthocord	Herculine	.000	.002	.721			
Surgeon	FiberWire	Ultrabraid	.000	.120	.000	.000	.418[c]	.000
		Orthocord	.194	.439	.484			
		Herculine	.000	.206	.001			
	Ultrabraid	Orthocord	.000	.423	.001			
		Herculine	.157	.761	.377			
	Orthocord	Herculine	.001	.617	.009			

[a] One-way analysis of variance. Means and SDs appear in Figures 3, 5, and 6.
[b] *P*>.0125.
[c] *P*>.05.

Load-to-Failure Test (3-mm Displacement)

There was no knot failure caused by suture breakage, suggesting that all knots failed by a combination of knot slippage and suture elongation. Figure 3 shows the mean ultimate clinical failure load of each of the sliding knots secured with a series of RHAPs and suture materials. There was a significant difference between the suture materials (*P*<.0125, Table I) and knot configurations (*P*<.0125, Table II). For each knot type, knots tied with Ultrabraid (mean, 299 N; SD, 35 N) showed significantly higher maximum load to failure compared with the other polyblend sutures. The Weston knot with 3 RHAPs using Ultrabraid provided the highest overall load to failure (mean, 346 N; SD, 24 N). Conversely, knots tied with Orthocord (mean, 233 N; SD, 36 N) had significantly lower load to failure than all the other polyblend sutures (*P*<.0125), with the exception of the surgeon knot.

Cyclic Loading Test

Figure 4 shows the mean elongation graphs for all knot configurations tested with different braided polyblend sutures. During cyclic loading from 6 N to 30 N for 1000 cycles, all knots displaced less than 0.45 mm (1.5% of original loop circumference) at the end of 1000 cycles. All knots also experienced higher suture slippage (elongation/number of cycles) at initial cyclic loading (50th cycles) followed by much lower suture slippage at increased numbers of cycles. Figures 5 and 6 compare the results for suture elongation at 50th cycle (initial) and 1000th cycle (final), respectively. At initial cyclic loading (50th cycles), there was no significant difference between suture materials except using Orthocord (Table I), and there was no significant difference between knot configurations except the static surgeon and Weston knots with 3 RHAPs (Table II). At final cyclic loading (1000th cycle), there was a significant difference across all suture and knot configurations ($P<.0125$). Analysis of the knot configuration and suture material revealed a significant difference caused by knot configuration (Table II) and a significant difference for knots tied with FiberWire and Ultrabraid (Table I).

The comparison of suture slippage using several braided polyblend sutures revealed an initial cyclic loading suture slippage around 2.3×10^{-3} mm/cycle (range, 1.6×10^{-3} to 3.1×10^{-3} mm/cycle). At increasing cycle numbers, it was found that samples tied with FiberWire and Orthocord exhibited about half the suture slippage (5×10^{-5} mm/cycle) of those tied with Herculine and Ultrabraid (11×10^{-5} mm/cycle). For knots tied with Herculine, no significant differences were found for knot and loop security using different types of sliding knots. However, knots tied with Ultrabraid demonstrated significant effects on knot and loop security using different types of sliding knots. As demonstrated in Figure 4, the Weston knot performed maximally with this type of suture material.

DISCUSSION

In this study, we evaluated biomechanical performance during load to failure and cyclic loading using different braided polyblend sutures with various sliding knot configurations. The results revealed that the Weston knot with 3 RHAPs using Ultrabraid provided superior performance compared with other combinations of knot configurations and different braided polyblend sutures in both load to failure and cyclic loading.

For a knot to be effective, it must have both knot security and loop security. Many combinations of knots and suture types have been devised to achieve a secure knot for optimal tissue apposition for healing, and, ultimately, to improve functional outcome.[7,10,11,13,20-22,24] Previous studies have evaluated knot security by determining the response to both load to failure and cyclic loading.[7,13,21,22,25-32] However, cyclic loading is more representative of the physiologic loads encountered as a result of repair reconstruction.[33] We based our study on parameters set forth in these studies, and we performed tests to determine whether certain suture configurations with a series of 3 RHAPs would provide better overall construct security during cyclic loading. Performance of the knot configurations and different braided polyblend sutures in this study was similar to that in other studies that used load-to-failure and cyclic loading protocols. Several studies examined loop security and tested various knot configurations.[4,9,14,34-36] Two studies found the Dines knot to be superior when compared with other configurations,[35,36] another study found the Samsung Medical Center (SMC) knot superior when compared with 3 other configurations,[34] and a fourth study reported the Roeder knot to be superior using 6-knot configurations.[4] The present study comprehensively assessed knot security using different braided polyblend sutures, and our findings were in agreement with the observation that suture knots and materials alter the force to clinical failure of comparable suture types.

Abbi and colleagues[37] compared 5 different knot configurations (Weston, Tennessee, Duncan, SMC, and San Diego knots, backed with 4 RHAPs) using No. 2 Ethibond (Ethicon, Somerville, New Jersey) and No. 2 FiberWire sutures under both cyclical and ultimate-failure loading patterns. They concluded that the most important factor affecting the tendency of knot slippage was the suture-surface characteristics and suture construction. Lieurance and colleagues[38] also concluded that a surgeon choosing arthroscopic repair techniques should be aware of the differences in suture material and the variation in knot strength afforded by different knot configurations. Mahar and colleagues[39] evaluated the performance of 3 knots (Duncan loop, Weston, and San Diego knots) with the use of 2 suture materials (No. 2 Ethibond, No. 2 Force Fiber) and found that suture material was one of the important aspects of loop security.

Our findings are in agreement with those of Abbi and colleagues,[37] Lieurance and colleagues,[38] and Mahar and colleagues[39] with respect to suture materials having a major effect on knot security even with a series of 3 RHAPs. In theory, these RHAPs should minimize suture friction, internal interference, and slack between loops of the knot, which emphasizes the effect of material selection. In addition, our findings indicated that different types of knot configurations can perform better using a particular type of suture material. The load-to-failure portion of this study led to several pertinent observations: (1) Every knot configuration tied using braided polyblend sutures reached clinical failure before ultimate failure; (2) Ultrabraid braided sutures performed better than others when tied with 5 commonly used complex sliding arthroscopic knots using a series of 3 RHAPs; (3) suture knots do alter the force to clinical failure in comparable suture types; (4) material properties of the suture can have an effect on knot holding capacity, thereby affecting the margin of safety in clinical practice.

Rotator cuff repairs can undergo up to 2000 cycles during a 6-week postoperative rehabilitation period, as shown by Wetzler and colleagues.[40] The stress on sutures used for soft-tissue repair depends on numerous factors, including tension required to bring edges together, length of repair, and number of sutures placed. Hence, the minimum stress resistance necessary to hold the repair until healing is difficult to define. Ideally, an arthroscopic knot should provide security equal to that of the time-honored openly tied square knot. However, it may be that even knots with less security hold long enough under physiologic stress to allow for healing to occur. Ilahi and colleagues[8] stated that arthroscopic soft-tissue repairs undergo many cycles of tensioning and relaxation before significant tissue healing occurs, and knot security under cyclic loads is essential for good results after these repairs. Those authors also concluded that post switching and reversal of loop direction are crucial to arthroscopic knot security. Elkousy and colleagues[9] concluded that all knots tested exhibited minimal elongation under cyclic loading test.

Cyclic load testing is another method for evaluating knot security. Previous studies have found small differences in knot performance using cyclic testing,[9,41] and the loop displacement values obtained in these studies were also small. This suggests that in a clinical setting there would be little chance of losing tissue apposition at repaired edges. All knotted loops experienced loop displacement at initial cyclic loading (50th cycles), possibly because of settling of the multiple loops in the initial loading that creates the higher suture slippage. We believe that, at higher cycles, the coefficient of friction of these sutures and the suture material starting to stretch may have caused the sliding knots to loosen. Although Ultrabraid has higher suture slippage than the other suture materials do, when this material is tied with the Weston knot, it increased the friction and reduced the stretch. This implies superior performance of the Weston knot tied with Ultrabraid during both load to failure and cyclic loadings. From the cyclic loading experiments, several observations also can be made: (1) Although the sliding knots performed well in load-to-clinical-failure tests, they may not perform as well under cyclic loading; (2) a higher number of cycles (>50) is a better evaluation of knot security, as suture slippage is expected at initial loading (<50 cycles) because of loop settling; (3) suture material types alter cyclic loading slippage of comparable suture knots. Our study results indicate that, even though these sutures are made of similar materials, different designs affect the fatigue life of the knot, thereby potentially affecting the margin of safety in clinical practice over the long run.

Our experimental design had certain limitations: (1) Knots were tied around a rigid smooth aluminum rod, and the suture loop did not pass through or over any soft tissue, turn acute angles, risk abrasion on suture anchors, or rub over bony surfaces; (2) knots were tied with no tension against the sutures, whereas, clinically, knots are tied under tension as tissues are pulled together in reconstructions; (3) the metal hooks used in this study are not compressible and do not interpose in the substance of the knot as soft tissue does in the clinical setting; (4) all arthroscopic knots were hand-tied, whereas, in the clinical setting, different techniques (eg, knot pusher) may result in knots that are not exactly similar to those in the laboratory setting; (5) the resident surgeon who tied the knots had limited clinical experience, and a more experienced surgeon might achieve different results; and (6) it was assumed that the loads measured during the cyclic loading tests were sufficient to cause loss of tissue approximation in vivo, but these loads may be larger than those required for a patient who has just undergone an arthroscopic shoulder repair and adheres to a passive motion protocol.

CONCLUSIONS

Our study results help further our understanding of the biomechanics of knot and loop security differences for different braided polyblend sutures. Overall, the Weston knot with 3 RHAPs using Ultrabraid provided the best loop and knot security in both the load-to-clinical-failure test and the cyclic loading test when compared with all other knot configurations and suture materials tested. Furthermore, we found that the tendency for knot slippage was much higher at the initial cyclic loading than at higher cycles. The findings of this investigation suggest that knot types and suture materials affect the balance of knot and loop security. In fact, the results of this study disproved the null hypothesis—that different braided polyblend sutures would not provide the same knot and loop security for different types of sliding knots in both load-to-failure and cyclic loading. Therefore, surgeons should be aware of the potential for knot slippage when selecting knot configurations and using particular suture material for arthroscopic rotator cuff repair. However, all the knot configurations in this study appear to be durable with respect to resistance to loosening under cyclic loading conditions.

AUTHORS' DISCLOSURE STATEMENT AND ACKNOWLEDGMENTS

The authors report no actual or potential conflict of interest in relation to this article.

The authors thank Arthrex, DePuy-Mitek, Linvatec Corp, and Smith & Nephew for providing the suture materials used in this study. We also thank Paul Wooley, PhD, for revising and offering critical comments on this article.

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