A Comparison of Knot Security and Loop Security in Arthroscopic Knots Tied With Newer High-Strength Suture Materials

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Purpose: The purpose of this study was to compare the knot security and loop security of 2 sliding and 1 static arthroscopic knot tied with different types of suture material. **Methods:** We evaluated 3 commonly used arthroscopic knots (surgeon's knot, Roeder knot, and Weston knot) tied with 6 different braided No. 2 sutures (FiberWire [Arthrex, Naples, FL]; Ethibond [Ethicon, Somerville, NJ]; Orthocord [DePuy Mitek, Raynham, MA]; Herculine [now called HiFi; ConMed Linvatec, Largo, FL]; MaxBraid [Arthrotek, Warsaw, IN]; and UltraBraid [Smith & Nephew, Andover, MA]). Each suture loop was then mounted on a materials testing system, 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:** We found that tying knots with different types of suture material can affect both the knot security and loop security of various types of arthroscopic knots. When a Roeder knot or surgeon's knot was tied, No. 2 FiberWire had the highest force to failure when compared with similar knots tied with other suture material ($P < .001$). The loop security for many of the knot and suture configurations was not significantly different. However, No. 2 FiberWire consistently showed the smallest loop circumference when compared with other suture materials. **Conclusions:** Arthroscopic knots tied with No. 2 FiberWire provide superior knot security and similar loop security compared with other commonly used high-strength polyethylene suture materials. **Clinical Relevance:** High-strength sutures exhibit unique mechanical characteristics that may vary significantly between suture types. In addition, knot configuration plays an important role in altering these characteristics as they relate to knot security.

Reconstructive arthroscopic shoulder surgery commonly requires creating a stable construct for soft-tissue healing to bone. Although a number of options exist, including knotless technology and suture welding, the most commonly used method of fixation still requires tying arthroscopic knots.[1,2] Recent studies comparing arthroscopic knots with hand-tied knots have shown arthroscopic knots to be equal, if not superior, to hand-tied knots for various knot configurations.[3-5] Optimization of tissue fixation by knot tying is therefore an important component of creating a stable construct.

For a knot to be effective, it must possess optimized 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 is dependent on 3 factors: friction, internal interference, and slack between throws.[6] Loop security is the ability to maintain a tight suture loop as a knot is tied.[6,7]

In a previous study, we showed that in addition to the type of arthroscopic knot, the type of suture can also affect the knot security and loop security of a construct.[8] The use of 1 type of high-strength suture material (i.e., No. 2 FiberWire [Arthrex, Naples, FL])

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increased knot security of most knots by a mean of 68.6%.[8] Since the publication of these data, a number of new high-strength suture types have become available. These suture types incorporate polyethylene in addition to other materials (e.g., polydioxanone, polyester, and polypropylene) to provide the suture with its intrinsic strength and properties. Recent suture types include FiberWire (multistranded long-chain ultrahigh–molecular weight polyethylene core and polyester braided jacket) (Arthrex); Orthocord (composite braided suture of polydioxanone and ultrahigh–molecular weight polyethylene) (DePuy Mitek, Raynham, MA); Herculine (braided ultrahigh–molecular weight polyethylene) (now called HiFi; ConMed Linvatec, Largo, FL); MaxBraid (braided ultrahigh–molecular weight polyethylene) (Arthrotek, Warsaw, IN); and UltraBraid (braided ultrahigh–molecular weight polyethylene) (Smith & Nephew, Andover, MA).

The purpose of this study was to compare the knot security and loop security of various arthroscopic knots tied with different types of high-strength suture material. We hypothesized that the new high-strength suture material would have knot and loop security superior to Ethibond (Ethicon, Somerville, NJ).

METHODS

We used 6 different braided No. 2 sutures: Ethibond (Ethicon), FiberWire (Arthrex), Orthocord (DePuy Mitek), Herculine (ConMed Linvatec), MaxBraid (Arthrotek), and UltraBraid (Smith & Nephew). By use of these 6 different types of suture materials, 2 sliding knots (the Roeder knot tied with 3 reversing half-hitches on alternating posts [RHAPs] and the Weston knot with 3 RHAPs) (Fig 1A) and a static 6-throw surgeon's knot were tied[8] (Fig 1B). The Roeder knot and Weston knot were chosen because our previous study showed that these 2 complex sliding knots provided the best balance of loop security and knot security of the commonly used arthroscopic knots.[8] The surgeon's knot comprised a stack of 3 half-hitches (base knot) followed by 3 consecutive half-hitches on alternating posts. Reversing the half-hitches and alternating the posts were performed by alternately tensioning the wrapping limbs with consecutive throws.[8] A total of 7 knots were tied for each possible combination of knots and sutures, for a total of 126 knots. The surgeon attempted to control the tension on each suture and knot by tactile feedback during knot tying.

Each knot was tied around a 30-mm-circumference plastic post to ensure a consistent loop circumference of 30 mm before "locking" the complex sliding knots

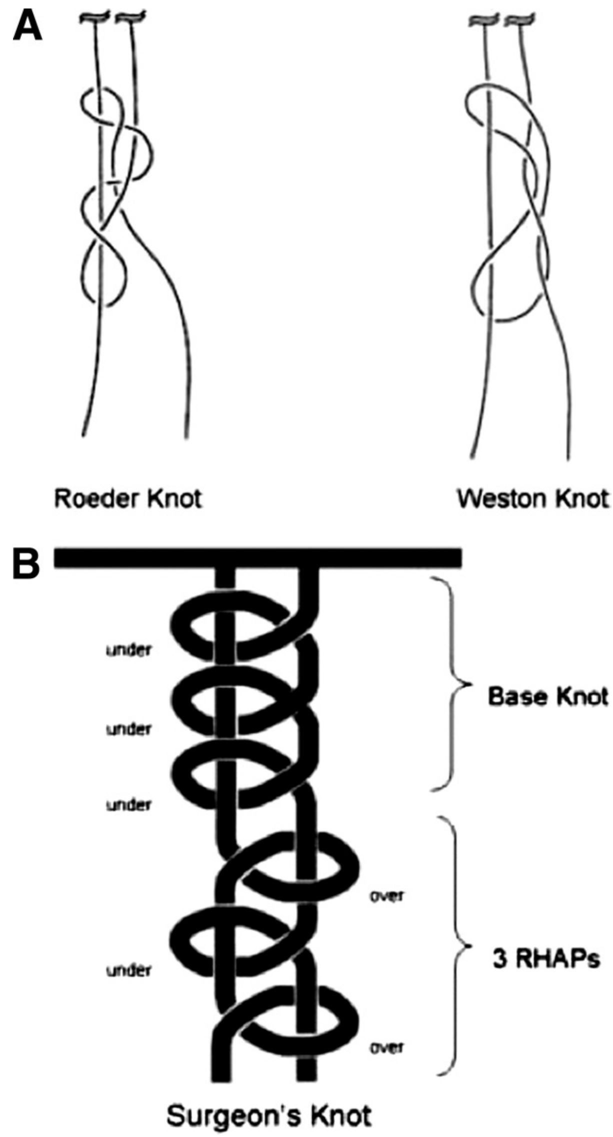

FIGURE 1. (A) Sliding knots. (B) Static knot.

by tensioning the wrapping limb of the suture. Each loop was then mounted on an Instron materials testing system (model 5544; Instron, Canton, MA) to test the knot and loop security of each knot (Fig 2). Fixtures were mounted to the base and crosshead of the Instron system with two 3.95-mm-diameter rods held parallel. Each loop was placed around the rods with the knots centered between the 2 rods. A 5-N preload was then applied at 1 mm/s followed by a pull to failure, also at 1 mm/s. Data were collected at 500 Hz.

The loop circumference was measured at the 5-N preload to assess each knot's ability to maintain a tight suture loop without slippage (loop security) and was

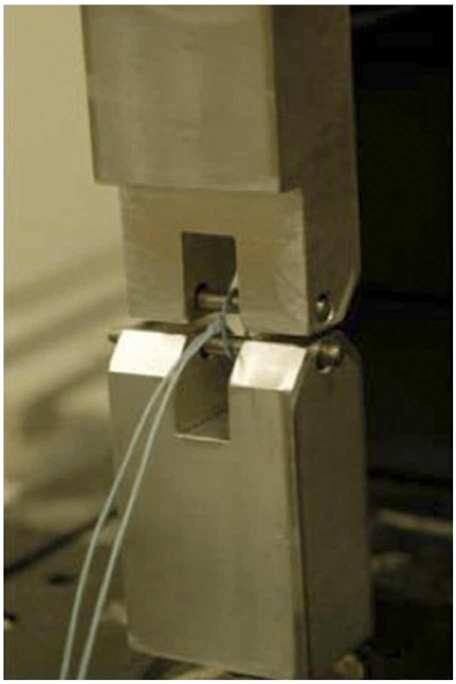

FIGURE 2. Testing apparatus with parallel rods attached to Instron system and mounted suture.

measured as previously described.[8] Loop security was measured as the maximum loop circumference at a 5-N preload. 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.

Knot security was measured as the maximum force to failure at 3 mm of crosshead displacement or suture breakage during single-pull load testing.[3] Three millimeters of crosshead displacement was chosen as failure, because this is the standard displacement for failure in most previous knot studies.[8-10] The maximum force to failure was recorded along with the mode of failure for each test.

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 also tested.[8] Seven specimens of each suture type were attached to the Instron system by use of pneumatic clamps set 30 mm apart. Each 30-mm gauge length of suture was pulled to failure at 1 mm/s, and data were recorded at 500 Hz. The yield load, ultimate load, and extension at yield were recorded. As an estimate of suture elongation, the amount of elongation that would occur at the maximum load of failure for each knot was calculated by use of the mean slope of each suture load-extension curve. Estimated knot slippage was therefore calculated as the residual amount of suture loop enlargement not accounted for by elongation.[8]

For statistical evaluation, 1-way analyses of variance were used. Post hoc pair-wise multiple comparisons were made with a Bonferroni *t* test. A significance level of .05 was used for all analyses.

RESULTS

Knot Security

None of the 126 knots tested in this study failed by suture breakage. That is, all knots failed by 3 mm of crosshead extension by a combination of suture elongation and knot slippage. Figure 3 includes the force to failure of each suture type and knot configuration.

When a surgeon's knot was tied, No. 2 FiberWire (185 ± 32 N) provided the greatest force to failure. The strength of the surgeon's knot tied with No. 2 FiberWire was significantly greater than that of all other sutures investigated in this study ($P < .001$). When a surgeon's knot was tied, among the other sutures, No. 2 Orthocord had the next highest force to failure (113 ± 18 N), followed by No. 2 Ethibond (102 ± 7 N), No. 2 Herculine (90 ± 43 N), No. 2 MaxBraid (70 ± 29 N), and No. 2 UltraBraid (63 ± 25 N). The force to failure of the surgeon's knot tied with No. 2 Orthocord was significantly greater than that with No. 2 UltraBraid ($P = .024$). There were no other significant differences among the other 4 sutures when a surgeon's knot was tied ($P > .05$).

When a Roeder knot was tied, No. 2 FiberWire (198 ± 29 N) provided the highest force to failure. The strength of the Roeder knot tied with No. 2 FiberWire was significantly higher than that of all

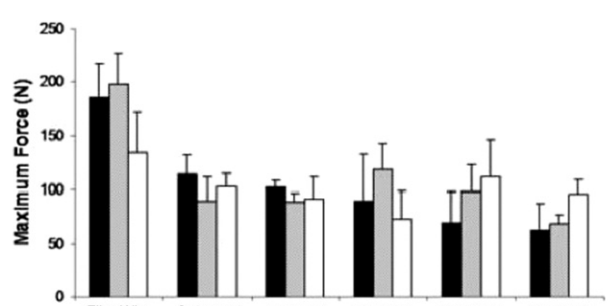

FIGURE 3. Maximum force to failure of surgeon's knot (a black box), Roeder knot (a gray box), and Weston knot (a white box) tied with various types of suture materials.

other Roeder knots tied with the other sutures investigated in this study ($P < .001$). Among the other sutures, No. 2 Herculine had the next highest strength (118 ± 25 N), followed by No. 2 MaxBraid (98 ± 25 N), No. 2 Orthocord (90 ± 22 N), No. 2 Ethibond (89 ± 8 N), and No. 2 UltraBraid (68 ± 9 N). There were no significant differences among these 5 sutures for Roeder knot force to failure ($P > .05$).

When a Weston knot was tied, No. 2 FiberWire (134 ± 38 N) provided the greatest force to failure, followed by No. 2 MaxBraid (112 ± 33 N), No. 2 Orthocord (103 ± 12 N), No. 2 UltraBraid (96 ± 13 N), No. 2 Ethibond (91 ± 21 N), and No. 2 Herculine (73 ± 27 N). The strength of the Weston knot tied with No. 2 FiberWire was significantly greater than that of the Weston knot tied with No. 2 Herculine ($P = .001$). There were no other significant differences among the Weston knots tied with the other suture types ($P > .05$).

Loop Security

The loop circumference of the surgeon's knot tied with No. 2 Orthocord (29.5 ± 0.2 mm) was the smallest. It was followed by No. 2 FiberWire (30.3 ± 0.5 mm), No. 2 Ethibond (30.4 ± 0.4 mm), No. 2 MaxBraid (30.4 ± 0.4 mm), No. 2 Herculine (31.0 ± 1.6 mm), and No. 2 UltraBraid (31.1 ± 1.4 mm). The loop circumference of the surgeon's knot tied with No. 2 Orthocord was significantly smaller than that of No. 2 UltraBraid ($P = .034$). There were no other significant differences between the loop circumferences of the surgeon's knots tied with all other sutures ($P > .05$). Figure 4 includes the loop circumference of each suture type and knot configuration.

The loop circumference of the Roeder knot tied with No. 2 FiberWire (31.0 ± 0.4 mm) and No. 2 Orthocord (31.0 ± 1.0 mm) was the smallest. They were followed by No. 2 Ethibond (31.8 ± 0.4 mm), No. 2 MaxBraid (31.9 ± 0.6 mm), No. 2 UltraBraid (32.1 ± 0.6 mm), and No. 2 Herculine (32.1 ± 0.9 mm). No significant differences existed for the loop circumference of Roeder knots tied with any of the 6 sutures ($P > .05$).

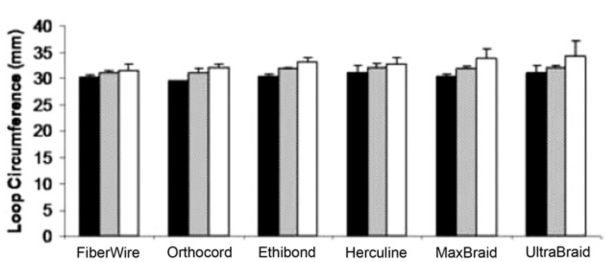

FIGURE 4. Loop circumference of surgeon's knot (a black box), Roeder knot (a gray box), and Weston knot (a white box) tied with various types of suture materials.

TABLE 1. *Yield Load, Percent Elongation at Yield Load, and Ultimate Load of Suture Materials During Straight-Pull Testing of Unknotted Lengths of Suture*

	% Elongation at Yield Load	Yield Load (N)	Ultimate Load (N)
FiberWire	10.7 ± 0.9	240 ± 14	283 ± 21
UltraBraid	24.0 ± 2.1	241 ± 8	241 ± 8
MaxBraid	26.5 ± 3.8	237 ± 19	237 ± 19
Herculine	22.5 ± 1.9	264 ± 20	264 ± 20
Orthocord	24.4 ± 1.5	210 ± 15	210 ± 15
Ethibond	27.5 ± 0.6	128 ± 3	128 ± 3

The loop circumference of the Weston knot tied with No. 2 FiberWire (31.5 ± 1.1 mm) was the smallest. This was followed by No. 2 Orthocord (32.1 ± 0.6 mm), No. 2 Herculine (32.7 ± 1.4 mm), No. 2 Ethibond (33.2 ± 1.0 mm), No. 2 MaxBraid (33.9 ± 1.8 mm), and No. 2 UltraBraid (34.3 ± 2.9 mm). The loop circumference of the Weston knot tied with No. 2 FiberWire was significantly lower than that of No. 2 UltraBraid ($P = .047$). No significant differences existed for the loop circumference of Weston knots tied with the other 4 suture types ($P > .05$).

Straight-Pull Testing

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 tested. The results are listed in Table 1. The percent elongation was calculated at the yield load because no suture slippage had occurred at the suture-clamp interface before the yield; that is, the load-extension curve was linear, validating the stiffness calculation for each curve.

The straight-pull ultimate strength of No. 2 FiberWire was significantly greater ($P < .001$) than that of all other sutures except for No. 2 Herculine ($P = .451$). The straight-pull ultimate strength of No. 2 Herculine, No. 2 UltraBraid, and No. 2 MaxBraid was also significantly greater than that of both No. 2 Ethibond and No. 2 Orthocord ($P < .05$). The straight-pull ultimate strength of No. 2 Orthocord was significantly greater than that of No. 2 Ethibond ($P < .001$). No other comparisons showed significant differences ($P > .05$).

The straight-pull percent elongation at yield of No. 2 FiberWire was significantly lower ($P < .001$) than that of all other sutures. Furthermore, the straight-pull percent elongation of No. 2 Herculine was significantly lower than that of both No. 2 Ethibond and No. 2 MaxBraid ($P < .01$). No significant difference existed for any other pair-wise multiple comparisons ($P > .05$).

Failure Mechanism

In this study no knots failed by suture breakage. Therefore all knots failed by a combination of suture elongation and knot slippage. The estimated amount of suture elongation and knot slippage for each knot and suture type are listed in Table 2. The surgeon's knot tied with No. 2 Ethibond had an estimated elongation of greater than 6 mm (and therefore a negative calculated knot slippage). This discrepancy can be accounted for by varying stress risers between a loop wrapped over 2 dowels and the pneumatic clamps used for straight pulls as previously published.[7]

The estimated slippage was greater than the estimated elongation for all No. 2 UltraBraid knots (surgeon's, Roeder, and Weston knots) and all No. 2 FiberWire knots (surgeon's, Roeder, and Weston knots). In contrast, the estimated elongation was greater than the estimated slippage for all No. 2 Ethibond knots (surgeon's, Roeder, and Weston knots) and No. 2 Orthocord knots (surgeon's, Roeder, and Weston knots). A combination of failure mechanisms was found for the No. 2 MaxBraid and No. 2 Herculine knots.

DISCUSSION

The concept of knot security has been shown in repeated studies to be an important fixation attribute for a variety of arthroscopic knots.[8-24] The most effective knots have the attributes of optimized knot security and loop security.[6,7,9] Although the knot configuration can significantly affect these attributes, knot security and loop security can also be affected by suture type, material, and instrumentation used to tie arthroscopic knots.[9,11-19,25-28] In addition, the configuration and number of RHAPs are essential to both loop and knot security of both sliding and non-sliding knots.[4,8,21,29] As in previous studies, newer-generation high-strength suture material has been shown to be stronger than standard contemporary suture material such as Ethibond, polydioxanone, or Nylon.[1,8,30] A recent study evaluating some high-strength suture material concluded that sliding knots were more secure than non-sliding knots.[31] To our knowledge, our study represents the only study of high-strength suture ma-

TABLE 2. *Estimated Failure Mechanisms by Suture Elongation or Knot Slippage of Arthroscopic Knots Tied With Each Type of Suture*

Suture	Failure Load (N)	Estimated Elongation (mm)	Estimated Elongation (%)	Estimated Slippage (mm)	Estimated Slippage (%)
Surgeon's knot					
FiberWire	185 ± 32	2.5 ± 0.5	41.3 ± 8.0	3.5 ± 0.5	58.7 ± 8.0
Orthocord	113 ± 18	4.0 ± 0.7	66.1 ± 11.5	2.0 ± 0.7	33.9 ± 11.5
Ethibond	102 ± 7	6.6 ± 0.4	109.7 ± 7.0	−0.6 ± 0.4	−9.7 ± 7.0
Herculine	90 ± 43	2.3 ± 1.2	39.0 ± 19.8	3.7 ± 1.2	61.0 ± 19.8
MaxBraid	70 ± 29	2.3 ± 1.0	38.4 ± 16.2	3.7 ± 1.0	61.6 ± 16.2
UltraBraid	63 ± 25	1.2 ± 0.8	31.5 ± 13.2	4.1 ± 0.8	68.5 ± 13.2
Roeder knot					
FiberWire	198 ± 29	2.7 ± 0.4	44.2 ± 7.1	3.4 ± 0.4	55.8 ± 7.1
Orthocord	90 ± 22	3.2 ± 0.9	52.9 ± 15.2	2.8 ± 0.9	47.1 ± 15.2
Ethibond	89 ± 8	5.7 ± 0.5	95.3 ± 8.9	0.3 ± 0.5	4.7 ± 8.9
Herculine	118 ± 25	3.0 ± 0.7	50.5 ± 11.8	3.0 ± 0.7	49.6 ± 11.8
MaxBraid	98 ± 25	3.3 ± 0.9	54.5 ± 14.2	2.7 ± 0.9	45.5 ± 14.2
UltraBraid	68 ± 9	2.1 ± 0.3	34.1 ± 5.7	4.0 ± 0.3	65.9 ± 5.7
Weston knot					
FiberWire	134 ± 38	1.8 ± 0.6	30.2 ± 9.4	4.2 ± 0.6	69.8 ± 9.4
Orthocord	103 ± 12	3.6 ± 0.6	60.1 ± 9.2	2.4 ± 0.6	39.9 ± 9.2
Ethibond	91 ± 21	5.9 ± 1.4	98.6 ± 23.4	0.1 ± 1.4	1.4 ± 23.4
Herculine	73 ± 27	1.9 ± 0.7	31.2 ± 11.9	4.1 ± 0.7	68.8 ± 11.9
MaxBraid	112 ± 33	3.7 ± 1.0	61.6 ± 16.6	2.3 ± 1.0	38.4 ± 16.6
UltraBraid	96 ± 13	2.9 ± 0.5	48.3 ± 8.3	3.1 ± 0.5	51.7 ± 8.3

NOTE. Direct comparison across suture types should not be made.

terial that analyzes both static and sliding-locking knots.

In this study we chose to measure the maximum force at clinical failure determined either by suture breakage or by crosshead displacement of 3 mm. In all cases crosshead displacement of 3 mm occurred before suture breakage, suggesting that the suture loops failed by a combination of knot slippage and suture elongation.

Loop security was measured as the loop circumference at a 5-N preload. Interestingly, surgeon's knots tied with No. 2 Orthocord had a mean loop circumference of less than the 30-mm post circumference (29.5 ± 0.2 mm). This unique characteristic has been previously observed.[31] This is likely because No. 2 Orthocord had a "bungee cord–like" effect, which enabled it to be tied under a tension greater than 5 N with a circumference less than 30 mm. Thus, when tested at a 5-N preload for loop security, the circumference was less than 30 mm. This phenomenon is similarly reflected by the estimated elongation of the surgeon's knot tied with No. 2 Orthocord (Table 2), which had an estimated elongation of 66% (the most elongation of all high-strength suture types, excluding Ethibond) and a force to failure that was 40% lower than that of No. 2 FiberWire. However, it should be noted that the surgeon's knot loop circumference was not significantly different for No. 2 Orthocord in comparison to No. 2 FiberWire ($P > .05$).

Under straight-pull testing of unknotted lengths of sutures, we found that No. 2 FiberWire has a greater ultimate strength (significantly so for all sutures except for No. 2 Herculine) at a significantly lower displacement than all competitors' sutures. These data suggest that using No. 2 FiberWire may provide a higher force to failure of knots as well as closer tissue apposition than other sutures at lower loads.

The goal of this study was to compare the biomechanical parameters of various high-strength suture materials using a well-established biomechanical model previously developed by us.[6,8] The strength of this model is that it isolates several variables and focuses on suture material and knot characteristics. A single pull to failure has been shown to generally cause knot failure rather than biologic tissue failure. Cyclic loading models more closely resemble normal postoperative rehabilitation conditions but have been shown to have a propensity to cause failure at the tissue-suture interface rather than by failure of the knot or suture material.[7] Therefore we decided to study a single pull to failure to isolate the suture knot as the weak link. Conversely, this study design has the weakness of not incorporating several clinically relevant characteristics, such as a wet environment, arthroscopic knot-tying abilities, and interaction between suture anchor and soft tissues. These factors have been shown in previous studies to affect outcomes.[25,26,31-33] In addition, the question of how much knot security is required is an important one. Previous studies by the senior author have shown that in vivo forces on a 4-cm cuff repair per suture vary between 38 and 60 N depending on the number of sutures and anchors.[6] Although FiberWire failed at between 134 and 198 N, 2 other high-strength suture materials failed at much lower levels (63 to 73 N), leaving a much smaller margin of safety to resist physiologic loads. Lastly, all knots failed by elongation rather than knot or suture breakage, suggesting that future knot configurations may provide more favorable results with higher-strength suture materials. This biomechanical study, therefore, provides essential information and perspective for future studies looking at cyclic loading and wet tissue environments.

CONCLUSIONS

Arthroscopic knots tied with No. 2 FiberWire provide superior knot security and similar loop security compared with other commonly used high-strength polyethylene suture material. The combination of suture composition and knot configuration plays an important role in altering loop security and knot security.

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