

An in vitro analysis of the mechanical properties of 16 arthroscopic knots

Keith M. Baumgarten · Michael D. Brodt ·
Matthew J. Silva · Rick W. Wright

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Abstract The purpose of this study was to determine the biomechanical characteristics of 16 arthroscopic knots and to determine if locking knots have superior loop security compared to non-locking knots. Sixteen knot types were tied in arthroscopic fashion and tested on a materials testing system. Knots were cyclically loaded to 30 Newtons (N) for 20 cycles and then loaded to failure at 1.25 mm/s. Ten samples of each knot were tied using both #2 Ethibond and #1 PDS II. Load to ultimate failure, load to clinical failure, post-cyclic stiffness, cyclical elongation, ultimate displacement, loop security, and mode of failure were determined for each knot. Nicky's Knot and the French Knot were most consistently ranked within the top five knot types for each of the biomechanical parameters. Locking knots did not improve loop security over non-locking knots.

Keywords Arthroscopy · Knots · Tying · Biomechanics

Introduction

An increasing number of surgeons are performing arthroscopic surgery. With the heightened popularity of arthroscopic surgery, the number of commonly used

arthroscopic knots has increased. The majority of arthroscopic surgeons use a knot learned from a mentor during training or learned from another surgeon during practice (unpublished data). Thus, most arthroscopic surgeons choose the knot they use based on empirical factors.

Upon review of the orthopaedic literature, there are many knots that are described, yet there are few studies available that compare the biomechanical properties of each arthroscopic knot [1–14]. The studies of Loutzenheiser et al. and Mishra et al. [11, 13, 14] were the first studies published that compared the biomechanical attributes of different arthroscopic knot configurations. Currently, the study that has compared the most number of knots head-to-head examined ten knots [4]. Two studies biomechanically compared six arthroscopic knots [9, 10], and two studies compared five different arthroscopic knots [1, 6]. Several studies biomechanically examined three knot configurations [2, 3, 5, 7, 12], and one study examined two different arthroscopic knot types [8]. These previously published studies did not provide a rational or inclusion and exclusion criteria for knots examined in each study.

To date, there has not been a systematic study that has examined the commonly used arthroscopic knots described in the literature and determined which knots have the best biomechanical parameters, as determined by (1) load to ultimate failure, (2) load to clinical failure (load at 3 mm elongation), (3) resistance to elongation under cyclic loads, and (4) ultimate displacement, (5) stiffness, (6) loop security (i.e., loop circumference at 5 N load), and (7) mode of failure using both absorbable and non-absorbable suture. In addition, a number of suture materials are available from which to choose. Two that have been commonly used in arthroscopic surgery are Ethibond and PDS. The purpose of this study is to determine which knots described in the orthopaedic literature have the best

K. M. Baumgarten (✉)
Sports Medicine and Shoulder Surgery Section,
The Orthopedic Institute, 810 E 23rd Street,
Sioux Falls, SD 57108, USA
e-mail: kbaumga@yahoo.com

M. D. Brodt · M. J. Silva · R. W. Wright
Department of Orthopaedic Surgery, Washington University
School of Medicine, 660 S. Euclid Ave, Campus,
Box 8233, St. Louis, MO 63110, USA

biomechanical parameters for each suture type in order to provide data to justify a scientific basis for knot selection for arthroscopic procedures.

The authors hypothesize that (1) the Double Twist Knot, a double suture loop knot, will have the best biomechanical characteristics of all the knots for both Ethibond and PDS suture and (2) locking knots will have superior loop security compared to non-locking knots.

Methods and materials

A review of the orthopaedic literature was performed to determine a comprehensive list of arthroscopic knots described in the literature. A Medline search provided references to 20 arthroscopic knots with sufficient instructions on knot tying technique. They included the Square Knot [15], Original Revo Knot [13, 16], Snyder's Knot [11], Revo Knot [6, 9, 15, 17], Overhand Throw [6, 11], the arthroscopic Duncan Loop [15, 18], French Knot [7], the Roeder Knot described by Nottage [15], Savoie-Modified Roeder Knot [9], Lieurance-Modified Roeder Knot [9], Tennessee Slider [15], Double Twist Knot [12], Nicky's Knot [19], Modified Taut Line Hitch [20], Field Knot [21], SMC Knot [22], Giant Knot [23], Weston Knot [24, 25], Snyder Slider [20], and Dines Slider [20].

Sixteen arthroscopic knots were chosen to undergo biomechanical evaluation. The Revo Knot was the only non-sliding arthroscopic knot included in the study. The sliding, non-locking arthroscopic knots included were: the arthroscopic Duncan Loop, French Knot, the Roeder Knot described by Nottage, Tennessee Slider, Double Twist Knot, Nicky's Knot, and the Modified Taut Line Hitch. The sliding, locking arthroscopic knots included were: the Savoie-Modified Roeder Knot, Lieurance-Modified Roeder Knot, Field Knot, SMC Knot, Giant Knot, Weston Knot, Snyder Slider, and Dines Slider.

The Overhand Throw was omitted because the authors believe that previous biomechanical studies have proven that it had significantly inferior strength properties compared to the other knots tested [6, 11]. The Original Revo Knot and Snyder's Knot were omitted because their half hitch configurations have been shown to be inferior to the half hitch configuration of the Revo Knot [26]. The arthroscopic Square Knot was omitted due to its propensity to convert to a biomechanically inferior half hitch configuration when tied arthroscopically [15]. However, a hand-tied Square Knot was used as a control in order to compare hand-tied knots to arthroscopic knots.

After initiation of this study, several more arthroscopic knots were described in the literature. These included the San Diego Knot [1, 27], the Hu Knot [28], the PC knot [29], the Tuckahoe Knot [30], the Inverse Knot [31], and

Table 1 Average force to ultimate failure and clinical failure comparing knots reinforced with 3 RHAPs to un-reinforced knots

	Knots reinforced with 3 RHAPs	Unreinforced knots	P value
Ethibond			
Average ultimate force to failure	126 ± 34.3	40.3 ± 27.4	<0.0001
Average clinical force to failure	103 ± 23.2	37.5 ± 27.9	<0.0001
PDS			
Average ultimate force to failure	120 ± 16.1	32.7 ± 15.2	<0.0001
Average clinical force to failure	65.8 ± 6.08	24.7 ± 13.8	<0.0001

the Triad Knot [32]. These were not included in this study since the study was in progress prior to their description in the accessible literature.

Each arthroscopic knot configuration was tied in the manner it was described in the orthopaedic literature. All but five of the knots in their initial literature description were reinforced with three reversed half hitches on alternating posts (3 RHAPs) as described by Loutzenheiser [14]. The five un-reinforced self-locking knots (Snyder Slider, Dines Slider, Giant Knot, SMC Knot, and Weston Knot) were reported in their initial literature description to not need half hitch reinforcement [20, 22–25]. We performed a pilot study that showed that reinforcement of these knots with 3 RHAPs significantly increased their biomechanical performance compared to the un-reinforced status (Table 1). Therefore, the authors reinforced these five knots with 3 RHAPs along with all the other knots for analysis in this study.

Ten knots of each type were tied arthroscopically using both monofilament, absorbable suture (#1 PDS II, Ethicon, Summerville, NJ) and braided, permanent suture (#2 Ethibond, Ethicon, Summerville, NJ) with a single hole knot pusher through an arthroscopic cannula. Each knot was tied around a smooth, one centimeter diameter rod. All knots were tied by a single investigator (KMB) and knot pusher force was maximized with each throw in order to tie each knot consistently. A tensiometer was not used because it is not used in clinical situations. Knots were removed from the rod, soaked in saline, and then placed on a jig on the Instron 8550R (Canton, MA) with a 200 lb. Lebow load cell (Troy, MI). The jig consisted of an open hook on one end and a steel rod fitted through two low-friction brass bushings on the other end. The rod rotated freely to ensure equal tension in both arms of the suture loop as the hook was displaced vertically (Fig. 1).

The biomechanical testing model was adapted from the technique of Mishra et al. [11] which included a pre-load

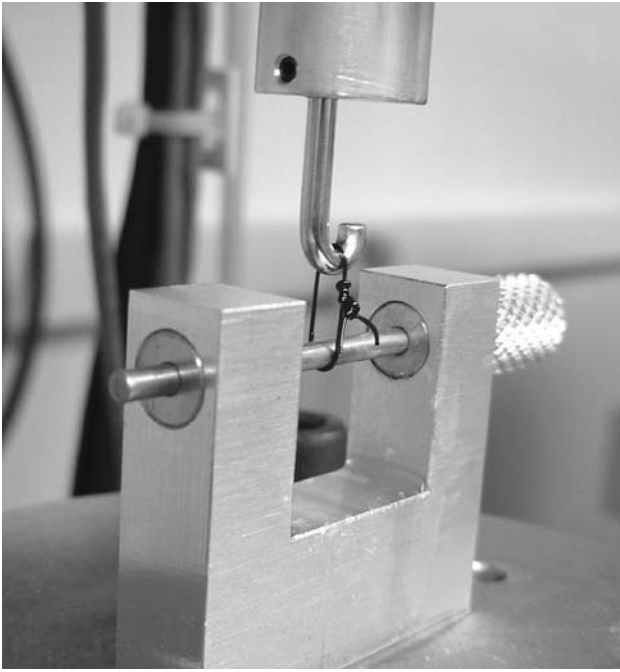


Fig. 1 A PDS suture loop placed on a jig on the Instron 8550R (Canton, MA). The jig consisted of an open hook and a rotating rod to minimize friction on the suture

phase, a cyclical loading phase, and an ultimate (failure) loading phase. All knots were first preloaded to 5 N to remove the slack and the loop length was recorded to calculate loop security. Loop security is a measure of the knot's ability to maintain a tight suture loop as the knot was tied [10, 14, 32] and was defined by the circumference of the loop at 5 N pre-load and was calculated by the formula described by Lo et al. [10]. The smaller the loop diameter correlates to greater loop security.

The preload was then increased to 10 N and the samples were loaded cyclically between 10 and 30 N at one Hertz for 20 cycles [11]. Following cyclical loading, the knots were immediately loaded to failure at a displacement rate of 1.25 mm/s [11, 14]. Mode of failure (knot pullout vs. suture breakage) was recorded for each test. Load to ultimate failure, load to clinical failure, cyclical elongation, stiffness during failure loading, ultimate displacement, and loop security were recorded for all knots. Load to clinical failure was defined as the force at a suture elongation of 3 mm (relative to the fixed, controlled original length) during the load to failure part of the test [14, 33, 35, 36]. Ultimate displacement was the amount of suture displacement that occurred at ultimate failure. Cyclical elongation was defined as the difference between the peak displacement of the 1st and 20th cycles (both measured at 30 N).

In addition to testing the suture loops, we also tested the material strength of the PDS and Ethibond suture. Loops of

suture material were tied (using a hand tied Modified Taut Line Hitch) and placed in the test fixture. Instead of the hook, a sandpaper covered fixed rod was used. The knot was placed over the fixed rod in such a way to protect it from failure during the test. The opposite end was placed over the rotating rod to allow equal tension. In all cases, the knot did not slip and the sample failed by rupture of one of the suture strands. The suture material strength was taken as the one-half the ultimate force to account for the two suture arms.

Data analysis

Data were recorded and analyzed with Labview 7.1 (National Instruments, Austin, TX). Statistically significant differences among knots tied with the same suture material were determined using the analysis of variance (ANOVA) on the ranked transformed data. If the ANOVA was statistically significant ($P < 0.05$) Tukeys post-hoc test was performed to determine which pairwise comparisons of means were significantly different. Analyses were performed using SAS version 8.2 (SAS Institute, Cary, NC).

Results

Ultimate failure

A statistically significant difference was found between knot types for load to ultimate failure using Ethibond suture ($P < 0.0001$) (Fig. 2) and PDS suture ($P < 0.0001$) (Fig. 3).

Clinical failure

A statistically significant difference was found between knot types for load to clinical failure (displacement = 3 mm) using Ethibond suture ($P < 0.0001$) (Fig. 4) and using PDS suture ($P < 0.0001$) (Fig. 5).

Loop security

A statistically significant difference was found between Ethibond knot types for loop security ($P < 0.0001$) (Fig. 6) and PDS knot types for loop security (Fig. 7).

Cyclical elongation, stiffness, and ultimate displacement

A statistically significant difference was found between knot types using both Ethibond (Table 2) and PDS suture (Table 3) for displacement after cyclical loading

Fig. 2 Average force to ultimate failure for Ethibond suture. *A* has a higher force to ultimate failure than *D, E, F, G, H, I* ($P < 0.05$). *B* has a higher force to ultimate failure than *F, G, H, I* ($P < 0.05$). *C* has a higher force to ultimate failure than *G, H, I* ($P < 0.05$). *D* has a higher force to ultimate failure than *H, I* ($P < 0.05$). *E* has a higher force to ultimate failure than *I* ($P < 0.05$)

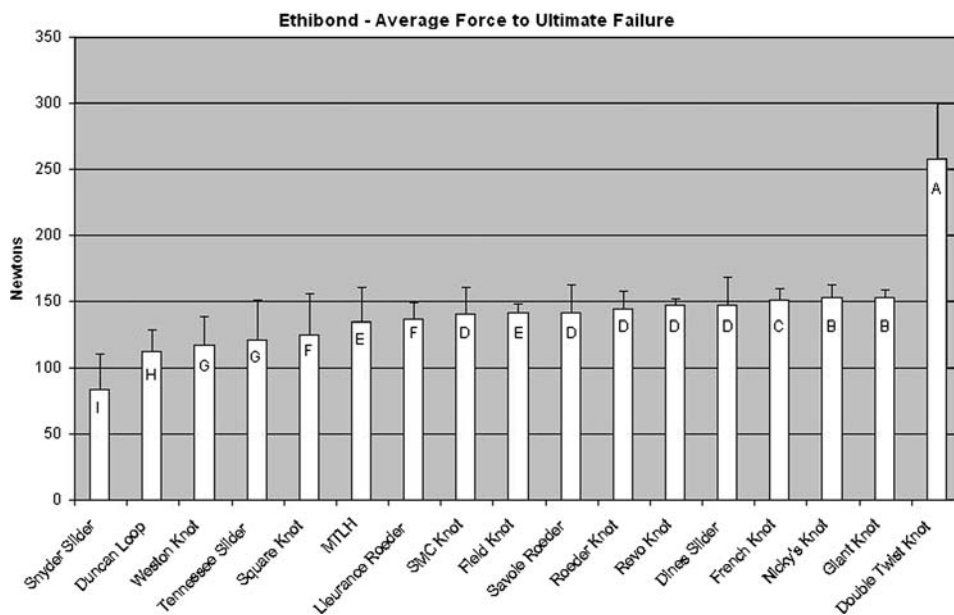
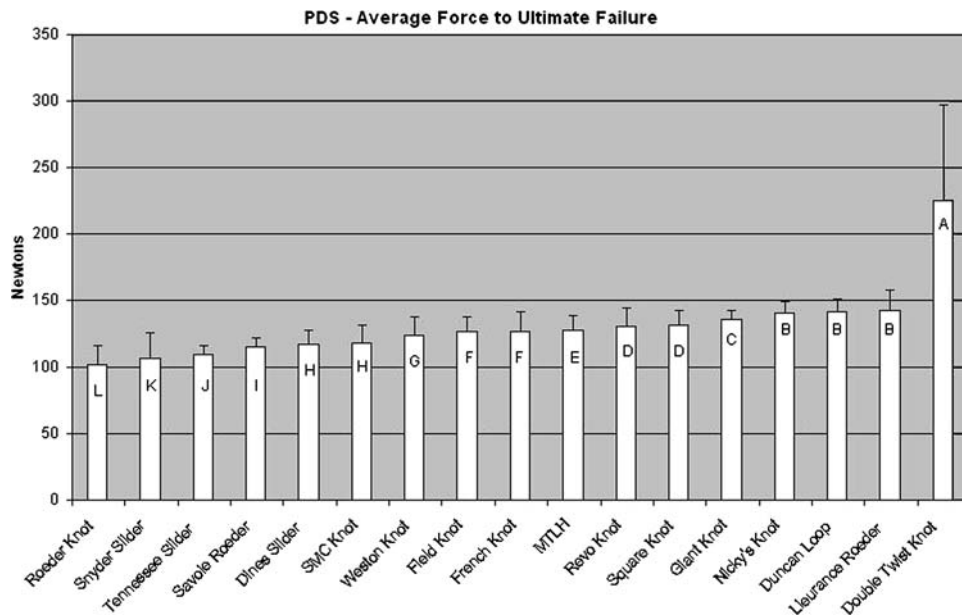


Fig. 3 Average force to ultimate failure for PDS suture. *A* has a higher force to ultimate failure than *F, G, H, I, J, K, L* ($P < 0.05$). *B* has a higher force to ultimate failure than *H, I, J, K, L* ($P < 0.05$). *C* has a higher force to ultimate failure than *I, J, K, L* ($P < 0.05$). *D* has a higher force to ultimate failure than *J, K, L* ($P < 0.05$). *E* has a higher force to ultimate failure than *J, L* ($P < 0.05$). *F* has a higher force to ultimate failure than *L* ($P < 0.05$)



(Ethibond $P = 0.0004$; PDS $P < 0.0001$), stiffness during failure loading ($P < 0.0001$), and ultimate displacement ($P < 0.0001$).

Failure mode

When a knot reached its ultimate load to failure, either the suture broke or the knot pulled out. Table 2 reveals the mode of failure for knots tied with Ethibond suture. The three knot types that had the lowest ultimate force to failure had the highest incidence of failure by knot pullout (Snyder Slider, Duncan Loop, Weston Knot).

Table 3 reveals the mode of failure for knots tied with PDS suture.

Suture material

Knots tied with Ethibond had superior loads to ultimate failure (141 ± 38.7 vs. 130 ± 32.2 N; $P = 0.005$), clinical failure (117 ± 29.1 vs. 73.4 ± 10.1 N; $P < 0.0001$), cyclical elongation (0.079 ± 0.036 vs. 0.182 ± 0.055 mm; $P < 0.0001$), stiffness (36.0 ± 11.9 vs. 16.8 ± 5.86 N/M; $P < 0.0001$), and ultimate displacement (3.95 ± 0.99 vs. 6.98 ± 1.38 mm; $P < 0.0001$) compared to knots tied with PDS. However, knots tied with PDS had superior loop security when compared to knots tied with Ethibond (28.5 ± 1.05 vs. 30.2 ± 0.65 mm; $P < 0.0001$).

In addition, the material strength properties of Ethibond and PDS suture were analyzed. Ethibond suture material

Fig. 4 Average force to clinical failure for Ethibond suture. A has a higher force to clinical failure than F, G, H, I ($P < 0.05$). B has a higher force to clinical failure than G, H, I ($P < 0.05$). C has a higher force to clinical failure than H, I ($P < 0.05$). D has a higher force to clinical failure than I ($P < 0.05$)

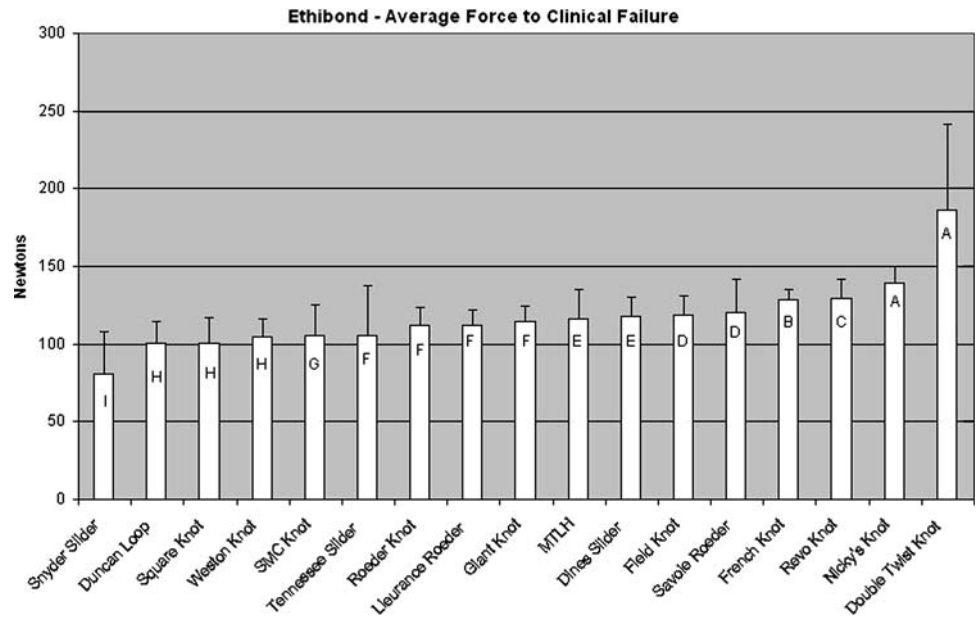
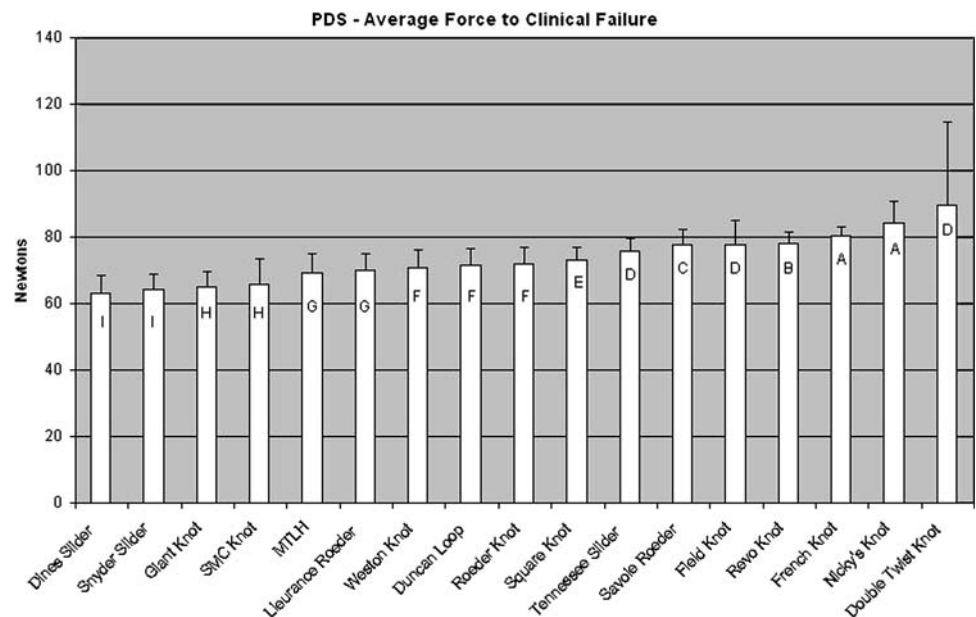


Fig. 5 Average force to clinical failure for PDS suture. A has a higher force to clinical failure than F, G, H, I, J ($P < 0.05$). B has a higher force to clinical failure than G, H, I, J ($P < 0.05$). C has a higher force to clinical failure than H, I, J ($P < 0.05$). D has a higher force to clinical failure than I, J ($P < 0.05$). E has a higher force to clinical failure than J ($P < 0.05$)



had significantly lower peak force to failure (73.3 ± 6.78 vs. 83.7 ± 4.90 N; $P = 0.0002$), but had higher stiffness (7.65 ± 0.959 vs. 3.93 ± 0.565 N/M; $P < 0.0001$), lower displacement at 10 N (0.856 ± 0.135 vs. 1.68 ± 0.447 mm; $P < 0.0001$) and 30 N (3.37 ± 0.407 vs. 6.48 ± 1.18 mm; $P < 0.0001$), and lower fracture displacement compared to the PDS suture material (9.13 ± 1.04 vs. 21.3 ± 4.00 mm; $P < 0.0001$).

For Ethibond suture, the knot with the highest mean ultimate load to failure (Double Twist Knot) had a 352% greater tensile strength compared to the suture material; whereas, the knot with the lowest mean ultimate load to failure (Snyder Slider) had a 115% greater tensile strength

compared to the suture material. For PDS suture, the knot with the highest mean ultimate load to failure (Double Twist Knot) had a 269% greater tensile strength compared to the suture material; whereas, the knot with the lowest mean ultimate load to failure (Roeder Knot) had a 122% greater tensile strength compared to the suture material.

Locking knots and loop security

Locking knots were not shown to have improved loop security when compared to non-locking knots for both Ethibond (30.2 ± 0.546 vs. 30.1 ± 0.765 mm; $P = 0.38$)

Fig. 6 Loop security for Ethibond suture. (the smaller the loop diameter correlates to improved loop security). A has significantly greater loop security than E, F, G, H ($P < 0.05$). B has significantly greater loop security than F, G, H ($P < 0.05$). C has significantly greater loop security than G, H ($P < 0.05$). D has significantly greater loop security than H ($P < 0.05$). E has significantly greater loop security than H ($P < 0.05$)

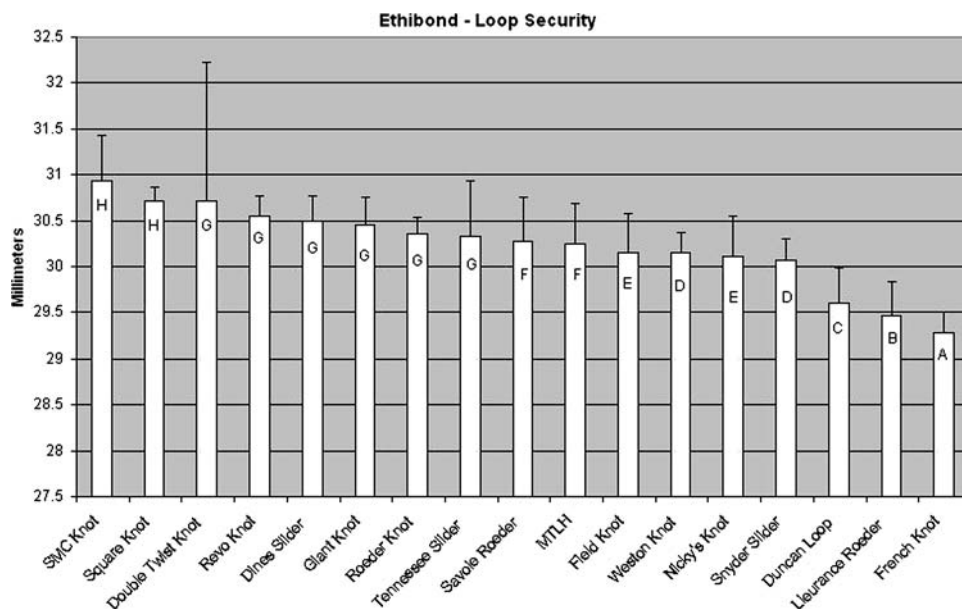
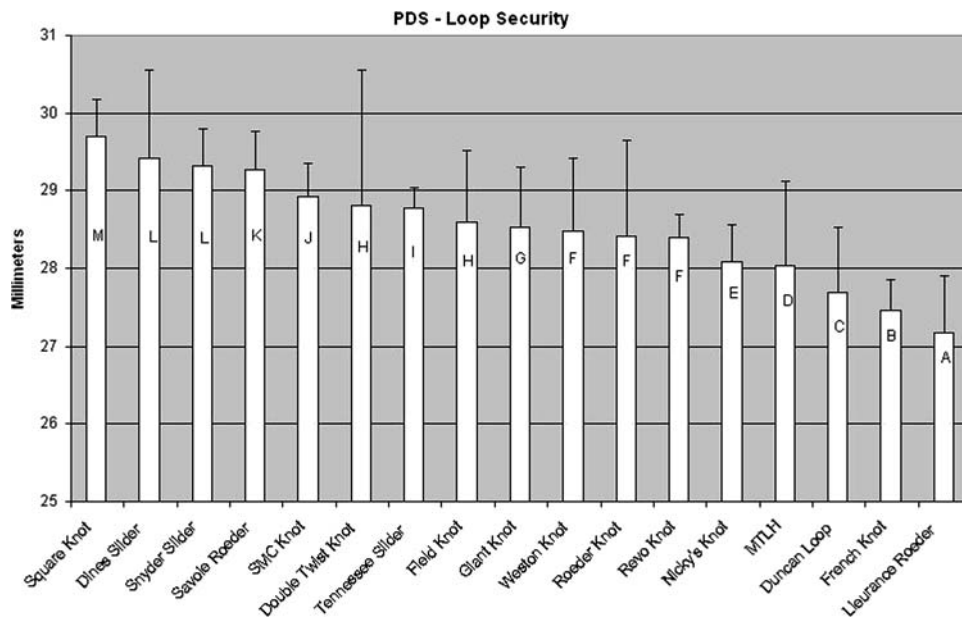


Fig. 7 Loop security for PDS suture. (the smaller the loop diameter correlates to improved loop security). A has significantly greater loop security than H, I, J, K, L, M ($P < 0.05$). B has significantly greater loop security than I, J, K, L, M ($P < 0.05$). C has significantly greater loop security than J, K, L, M ($P < 0.05$). D has significantly greater loop security than K, L, M ($P < 0.05$). E has significantly greater loop security than L, M ($P < 0.05$). F has significantly greater loop security than M ($P < 0.05$)



and PDS sutures (28.7 ± 1.01 vs. 28.3 ± 0.989 mm; $P = 0.002$).

Discussion

The goal of this study was to determine the biomechanical parameters of the arthroscopic knots described in the orthopaedic literature and assist the surgeon in choosing a knot to use based on each knots biomechanical features. The current study showed that the Double Twist Knot was superior to all other knots when evaluating ultimate load, load to clinical failure, and stiffness for both PDS and

Ethibond sutures. Nevertheless, there are some limitations of the Double Twist Knot. First, the Double Twist Knot did not show superior performance compared to the other knot configurations when examining two important pre-failure measures—loop security and cyclic elongation (for both Ethibond and PDS). In addition, the Double Twist Knot requires custom-made suture anchors since it is a double-stranded knot, and only allows for one knot per suture anchor. When using most of the other knot configurations in this study that allow for two knots per suture anchor, the additive effect of the two knots should provide a force to ultimate failure and clinical failure that are equal to or greater than that of the Double Twist Knot.

Table 2 Biomechanical analysis of ethibond suture

	Cyclic elongation (mm)		Post cyclic stiffness (N/m)		Ultimate displacement (mm)		Failure mode
	Mean	SD	Mean	SD	Mean	SD	% of knot breakage
Dines Slider	0.077 ^B	0.028	34.16 ^d	5.06	4.122 ^{EE}	0.394	63
Double Twist Knot	0.094 ^B	0.049	62.99 ^a	16.33	4.675 ^{EE}	1.371	100
Duncan Loop	0.094 ^C	0.022	28.19 ^f	5.07	3.609 ^{CC}	0.716	0
Field Knot	0.077 ^B	0.041	34.18 ^d	3.90	4.831 ^{GG}	0.931	90
French Knot	0.074 ^B	0.017	41.72 ^b	3.52	3.663 ^{DD}	0.123	90
Giant Knot	0.083 ^C	0.021	33.27 ^d	3.23	4.370 ^{FF}	0.488	100
Lieurance Roeder	0.082 ^C	0.012	33.43 ^d	4.86	4.187 ^{EE}	0.642	90
MTLH	0.066 ^B	0.010	33.64 ^d	6.61	3.798 ^{EE}	0.432	60
Nicky's Knot	0.052 ^A	0.014	42.69 ^b	5.05	3.573 ^{CC}	0.180	80
Revo Knot	0.068 ^B	0.018	39.99 ^c	7.51	3.671 ^{DD}	0.440	90
Roeder Knot	0.080 ^B	0.023	32.90 ^d	3.98	4.646 ^{FF}	0.936	78
Savoie Roeder	0.073 ^B	0.022	36.26 ^d	8.75	3.900 ^{EE}	0.860	90
SMC Knot	0.100 ^C	0.058	30.68 ^e	6.55	4.450 ^{EE}	1.553	70
Snyder Slider	0.113 ^B	0.089	35.64 ^e	27.52	2.568 ^{AA}	0.436	10
Square Knot	0.063 ^B	0.014	29.40 ^f	3.73	4.138 ^{EE}	1.297	50
Tennessee Slider	0.065 ^B	0.016	33.13 ^d	10.94	3.445 ^{BB}	1.396	67
Weston Knot	0.090 ^C	0.019	29.99 ^f	3.92	3.608 ^{DD}	0.604	22

Cyclical elongation

^A Significantly less elongation after cyclical loading than C ($P < 0.05$)

Post-cyclic stiffness

^a Significantly greater post-cyclic stiffness than d, e, f ($P < 0.05$)

^b Significantly greater post-cyclic stiffness than e, f ($P < 0.05$)

^c Significantly greater post-cyclic stiffness than f ($P < 0.05$)

Ultimate displacement

^{AA} Significantly less ultimate displacement than EE, FF, GG ($P < 0.05$)

^{BB} Significantly less ultimate displacement than FF, GG ($P < 0.05$)

^{CC} Significantly less ultimate displacement than GG ($P < 0.05$)

The French Knot and Nicky's Knot ranked consistently within the top knot configurations for the biomechanical parameters evaluated in this study (Table 4). We evaluated seven biomechanical parameters for each knot type including: (1) force to ultimate failure, (2) force to clinical failure, (3) cyclical elongation, (4) post-cyclic stiffness, (5) ultimate displacement, (6) loop security, and (7) failure mode. Nicky's Knot was ranked in the top five knot configurations for six of the seven biomechanical parameters for both Ethibond and PDS. The French Knot ranked in the top five knot configurations for five of the seven biomechanical parameters for both suture types. In addition, the French Knot along with the Lieurance Roeder had the best loop security of all the knots tested for both Ethibond and PDS suture. Thus, the authors recommend the use of either the French Knot or Nicky's Knot when choosing a sliding knot to use in arthroscopic surgery. When using PDS specifically, the Field Knot performed well in five out of the seven biomechanical parameters and may be considered.

Using a theoretical determination of maximal muscle contraction of the rotator cuff, Burkhart et al. [33] determined that if a rotator cuff repair was performed using double-loaded suture anchors placed one centimeter apart that each knot configuration must be able to bear 37.7 N of force. If this theory is clinically accurate, our study suggests that each knot configuration tested for both suture materials is sufficiently strong enough for rotator cuff repair when analyzing force to ultimate failure and clinical failure. Nevertheless, we continue to recommend the use of the knots found to have the best biomechanical attributes (French Knot and Nicky's Knot) for several reasons. First, the 37.7 N threshold is a theoretical determination that has not yet been supported clinically. Second, this theory is based on maximal muscle contraction and does not account for higher loads that may be seen if the postoperative shoulder is subjected to an unanticipated traumatic force. Third, this theory does not account for initial loop security of the knots or the ability to resist elongation under cyclic loading. If a knot can maintain 37.7 N of ultimate or

Table 3 Biomechanical analysis of PDS suture

	Cyclical elongation (mm)		Post cyclic stiffness (N/m)		Ultimate displacement (mm)		Failure mode
	Mean	SD	Mean	SD	Mean	SD	% of knot breakage
Dines Slider	0.199 ^H	0.030	14.00 ^d	1.58	7.377 ^{GG}	0.707	100
Double Twist Knot	0.169 ^D	0.057	36.92 ^a	6.16	6.851 ^{EE}	1.857	78
Duncan Loop	0.183 ^F	0.038	14.46 ^d	1.16	7.967 ^{HH}	1.024	100
Field Knot	0.153 ^C	0.028	17.34 ^b	3.52	6.433 ^{DD}	0.869	100
French Knot	0.171 ^E	0.027	17.63 ^b	2.36	6.090 ^{CC}	1.170	100
Giant Knot	0.281 ^K	0.075	14.12 ^d	1.55	8.106 ^{HH}	0.736	100
Lieurance Roeder	0.219 ^J	0.027	14.33 ^d	2.92	8.509 ^{II}	1.209	90
MTLH	0.189 ^F	0.054	12.75 ^e	3.00	8.077 ^{HH}	1.100	80
Nicky's Knot	0.139 ^A	0.037	18.90 ^b	4.31	6.720 ^{DD}	0.685	100
Revo Knot	0.163 ^E	0.024	16.40 ^d	3.14	6.763 ^{EE}	1.121	100
Roeder Knot	0.174 ^F	0.025	16.88 ^c	3.63	5.450 ^{BB}	1.487	78
Savoie Roeder	0.144 ^B	0.022	17.43 ^b	3.13	5.932 ^{CC}	0.470	100
SMC Knot	0.192 ^G	0.038	14.03 ^d	1.71	7.272 ^{EE}	1.277	90
Snyder Slider	0.242 ^I	0.112	14.76 ^d	2.52	7.498 ^{GG}	1.838	80
Square Knot	0.153 ^D	0.020	15.65 ^d	2.49	7.309 ^{FF}	0.238	100
Tennessee Slider	0.147 ^B	0.020	16.03 ^d	3.41	5.587 ^{AA}	0.693	100
Weston Knot	0.190 ^G	0.033	15.60 ^d	1.80	6.878 ^{EE}	1.087	60

Cyclical elongation

^A Significantly less elongation after cyclical loading than G, H, I, J, K ($P < 0.05$)

^B Significantly less elongation after cyclical loading than H, I, J, K ($P < 0.05$)

^C Significantly less elongation after cyclical loading than I, J, K ($P < 0.05$)

^D Significantly less elongation after cyclical loading than J, K ($P < 0.05$)

^E Significantly less elongation after cyclical loading than K ($P < 0.05$)

Post-cyclic stiffness

^a Significantly greater post-cyclic stiffness than c, d, e ($P < 0.05$)

^{b, c} Significantly greater post-cyclic stiffness than e ($P < 0.05$)

Ultimate displacement

^{AA} Significantly less ultimate displacement than FF, GG, HH, II ($P < 0.05$)

^{BB} Significantly less ultimate displacement than GG, HH, II ($P < 0.05$)

^{CC} Significantly less ultimate displacement than HH, II ($P < 0.05$)

^{DD} Significantly less ultimate displacement than II ($P < 0.05$)

clinical force to failure but cannot maintain a tight initial loop, than the tendon repair construct may loosen and failure may occur through the tendon–suture interface. Lastly, multiple studies have shown that there may be a high rate of rotator cuff repair failures after arthroscopic surgery (12–95%) [37–41]. Therefore, we recommend using the knot configurations with the best biomechanical properties to attempt to reduce the risk of repair failure.

The importance of loop security was initially emphasized by Burkhart et al. [34] and further examined in other studies [2, 4, 5, 10]. Loop security is the measure of tightness of the suture loop. A loose suture loop will not hold tissue apposed regardless of the force to ultimate failure. The method of Lo et al. [10] was used to determine

loop security. A commercially available 1 cm diameter smooth rod was used to standardize the circumference of each suture loop prior to placement on the material testing system. Using precision calipers, the actual diameter of the rod was measured at 9.8 mm. Therefore, the optimal loop circumference was calculated to be $9.8 \text{ mm} * \pi = 30.8 \text{ mm}$.

Interestingly, our data indicate that all knot configurations except for the SMC knot tied with Ethibond suture had a mean loop security (circumference at 5 N) less than the circumference of the dowel around which the knots were tied. Moreover, the difference between loop security and dowel circumference was greater for PDS specimens than for Ethibond specimens. This unexpected finding was likely due to a pre-tensioning effect whereby the suture was

Table 4 The number of times each knot ranked in the top 1/3 tier for each of the seven biomechanical parameters assessed (force to ultimate failure, force to clinical failure, loop security, cyclical elongation, post-cyclic stiffness, ultimate displacement, and failure mode)

Top 1/3 tier	# of biomechanical parameters (7 possible)	
	Ethibond	PDS
Nicky's Knot	6	6
French Knot	5	5
Double Twist Knot	4	3
Revo Knot	3	2
Duncan Loop	2	3
Giant Knot	2	2
Lieurance Roeder	2	2
Savoie Roeder	2	4
Tennessee Slider	2	3
Snyder Slider	2	0
Dines Slider	1	1
Field Knot	1	5
MTLH	1	1
Square Knot	1	2
Weston Knot	1	0
Roeder Knot	0	1

stretched during knot tying, causing the loop to shorten when it was removed from the dowel. Assuming that there was no systematic difference in the amount of tensile force applied during knot tying, the less stiff PDS suture would have stretched more, and thus would have shortened more when taken off the dowel compared to the Ethibond suture. This would account for the significant difference in loop security between PDS and Ethibond specimens. Despite the pretensioning/shortening issue, the relative differences in loop security between the different knots and suture materials are still valid.

Although this shortening of the suture due to pretensioning was not found in the study of Lo et al. [10], it was described in the initial manuscript of Burkhart et al. on loop security [34]. We hypothesize that similar findings were not described in the model of Lo et al. [10] because the knots in that study were tied by hand. We suggest that hand knot tying does not allow the degree of knot and suture tensioning that occurs when tying knots with a knot pusher. Our study supports this hypothesis because the hand-tied square knot had inferior loop security measurements compared to arthroscopically tied knots for both Ethibond and PDS suture.

There were several limitations to this study. First, the biomechanical analysis was performed *in vitro*. It did not reproduce or assess for failure at the tendon–suture–tendon interface or the bone–suture anchor–suture–tendon

interface found *in vivo*. Knots were tied dry through an arthroscopic cannula in an artificial environment. This could lead to suture abrasion which could cause premature knot breakage. Second, it is not possible to identify a single knot as absolutely superior to other knots, as there is no single parameter that will predict optimal *in vivo* performance. Of the parameters we reported, we believe that loop security, cyclic elongation and force to clinical failure are of special importance as they provide measures of the knot performance at low force loading. Nevertheless, we are not aware of a consensus opinion on which parameter set is most important. Another limitation of this study was that it did not assess the biomechanical characteristics of the relatively new second-generation suture, that is being used more frequently in arthroscopic rotator cuff repairs.

Conclusions

The French Knot and Nicky's Knot ranked consistently within the top knot configurations for the biomechanical parameters evaluated in this study. Self-locking knots did not have superior loop security compared to non-locking knots. Lastly, this study supports the concept that all arthroscopic knot configurations should be reinforced with 3 RHAPs.

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