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ORIGINAL ARTICLE - RESEARCH

WILEY

In vitro evaluation of the modified forwarder knot used to end a continuous suture pattern in large-gauge suture

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Abstract

Objective: To evaluate the strength and size of forwarder end (FE) knots modified to end continuous suture lines compared with Aberdeen (AB), square (SQ), and surgeon's (SU) knots.

Study design: In vitro mechanical study.

Study population: Knotted suture.

Methods: Knots were tied with 2 USP (United States Pharmacopeia) polydioxanone, 2 USP, and 3 USP polyglactin 910 and tested on a universal testing machine under linear tension. Mode of failure and knot holding capacity (KHC) were recorded, and relative knot security (RKS) was calculated. Knot volume and weight were determined by digital micrometer and balance. Knot holding capacity, RKS, size, and weight between knot type, number of throws, and suture type and size were compared by using analysis of variance testing, with $P < .05$ considered significant.

Results: In all suture types and number of throws, FE knot KHC/RKS was 28% to 66.99% (1.2-1.6 fold) stronger compared with SQ/SU knots ($P < .001$). For 2 USP polydioxanone, FE knots had 10% (1.1 fold) higher KHC/RKS compared with AB knots ($P < .042$). However, in 2 and 3 USP polyglactin 910, FE knot KHC/RKS values were not different from those of AB knots ($P > .080$). Forwarder end/AB knots failed by suture breakage at the knot, whereas some SQ/SU knots unraveled. Forwarder end knots in 2 and 3 USP polyglactin 910 were 21.1% to 44.4% (1.2-1.4 fold) smaller compared with SQ/SU knots ($P < .028$). Forwarder end knots in 2 and 3 USP polyglactin 910 were 40% to 99% (1.4-2.0 fold) larger compared with AB knots ($P < .001$).

The results of this work were presented in part as a poster at the American College of Veterinary Surgeons Surgery Summit; October 16-19, 2019; Las Vegas, Nevada.

Conclusion: Forwarder end knots provided increased KHC/RKS compared with SQ/SU knots.
Clinical relevance: Forwarder end knots should be considered for closures when suture is placed under tension.

1 | INTRODUCTION

Complete incisional dehiscence and subsequent eventration is a potentially fatal complication which can occur following ventral midline celiotomy. Dehiscence of the linea alba is relatively infrequent; in a study of 161 horses that underwent a ventral median celiotomy, 1% experienced complete dehiscence, and another 1% suffered from partial dehiscence.[1] Common causes of dehiscence are tissue failure and suture-related failures, including loss of suture strength, suture breakage, and knot failure.[2]

Surgeons frequently choose to use a simple continuous suture pattern to close ventral median celiotomies, and this pattern has been shown to be stronger than the inverted cruciate pattern.[3] For a simple continuous suture pattern, the start and end knots are critical to ensure the security of the suture line. In studies in which the biomechanics of several suture types and sizes in the equine linea alba were examined, the cause of closure failure was most frequently due to knot failure, which occurred in 80%[4], 90.4%[5], and 93%[6] of the specimens. The findings of these studies provide evidence of the importance of appropriate knot construction for security of the closure. Square (SQ) and surgeon's (SU) knots are most frequently used in equine practice and have been found to have the greatest strength when the surgeon uses at least six throws for a start knot and at least seven throws for an end knot using large-gauge suture.[7] However, additional throws make the knots larger, which can cause greater tissue reaction.[8] Therefore, the ideal knot maximizes strength while minimizing size.

The Aberdeen (AB) knot, a self-locking knot, has previously been investigated as an alternative for terminating a continuous suture pattern. While the AB knot was found to be significantly stronger and smaller than both SQ and SU knots when tied with large-gauge suture,[9] surgeons may struggle to maintain appropriate tension on the continuous suture line because of the knot's self-tightening mechanism, which can introduce extra slack into the suture line.[10] Another self-locking knot, the forwarder knot, has been tested as an initiation knot in large-gauge suture, where it has been shown to be stronger and smaller than the SQ and SU knots.[11] Unlike the AB knot, the forwarder knot can be adjusted after it has been tied to maintain appropriate tension on the line. However, the forwarder knot cannot be used as an end knot in its current form because of the fact that only the working end of the suture is locked. Therefore, the development of an end-knot variation of the forwarder knot may provide a stronger knot that does not sacrifice suture line tension and would also allow for completion of a continuous suture line.

The objective of this study was to evaluate this modification of the forwarder knot for use as an end knot in comparison to the AB, SU, and SQ knots with large-gauge suture, specifically 2 polydioxanone and 2 and 3 polyglactin 910. We hypothesized that the forwarder end (FE) knot would have significantly greater knot holding capacity (KHC) and relative knot security (RKS) compared with both the SU and SQ knots but would have comparable KHC and RKS values compared with the AB knot. Also, we hypothesized that the FE knot would be of similar size and weight compared with SU and SQ knots but would be larger than the AB knot when the same number of throws were applied.

2 | MATERIALS AND METHODS

Testing was performed at the Auburn University Fiber and Polymer Engineering Laboratory in controlled conditions of 20°C ± 2°C and 65% ± 5% relative humidity. Researchers in a previous study[11] evaluated three board-certified surgeons while tying SU knots and found the average force applied to be 21 N. This force was established as the static preload for all testing.

To ensure suture uniformity, the tensile strength of one suture strand from each box was tested in a single, cycle-to-failure test. Each suture was distracted by using a universal testing machine (Series 5565; Instron, Norwood, Massachusetts) at 20 mm/minute with a static preload of 21 N ± 0.01%, based on the established standard force. Any suture with a tensile strength difference greater than 10% of the mean tensile strength was considered defective, and the corresponding box of suture was removed from the study.[12] The suture types used were 2 USP (United States Pharmacopeia) polyglactin 910, 3 USP polyglactin 910, and 2 USP polydioxanone. The equipment set-up and protocol were the same as those used in a previous study.[11]

All knots were tied by the same operator (A.G.) around a smooth, vertical bar. As would be generally performed by using conventional surgical methods, 8-in Mayo-Hegar needle holders were used to grasp a loop of suture to tie both SQ and SU knots. Square knots consisted of only single throws, while the SU knots first used a double overhand throw, followed by single throws. Both SQ and SU knots were tied with throws ranging from four to eight throws with 10 knots for each suture type, resulting in 150 knots of each knot type.

Similarly to the SQ and SU knots, the AB knot is started by forming a loop in the suture and passed around the stand. A second loop is formed and passed through the first loop. This pattern is a complete throw and can be repeated as desired by the surgeon. To complete the knot, either one or two turns are added, in which the working end of the suture is passed through the second loop of the final throw. In this study, throws ranged from three to six throws, and 10 knots were tied in each suture type, resulting in a total of 240 AB knots.

To perform an FE knot, a loop of suture was passed around the stand. The free end of the suture loop was held parallel to the needle holders while the free single strand was wrapped around both the suture loop and the needle drivers; the number of complete wraps is equivalent to the number of throws. After the number of desired throws was achieved, the end of the loop was grasped by the tip of the needle drivers and pulled away from the stand through the loops formed by the throws to complete the knot. The direction of the needle drivers was then reversed, and the loop was wrapped around both the free suture end and the needle drivers (Figure 1). Throws ranged from three to five in each direction, and 10 knots were tied in each suture type, resulting in 90 FE knots. The FE knot was not tested with more than five throws, on the basis of a pilot study in which knots with ≥6 throws in each direction were not able to maintain separation of the loops to form a tight knot. The SQ and SU knots were tied first, followed by AB knots, and finally FE knots. The knots were tied over a 10-day period.

All knots were removed from the stand and visually inspected to ensure proper tying technique. If found to be unsatisfactory due to gaps between throws or asymmetry, the knot was discarded and a replacement knot of the same type was tied with a new length of suture. The free end that did not represent the continuous suture line was trimmed to 3 mm by using a digital micrometer to detect knot slippage during distraction.

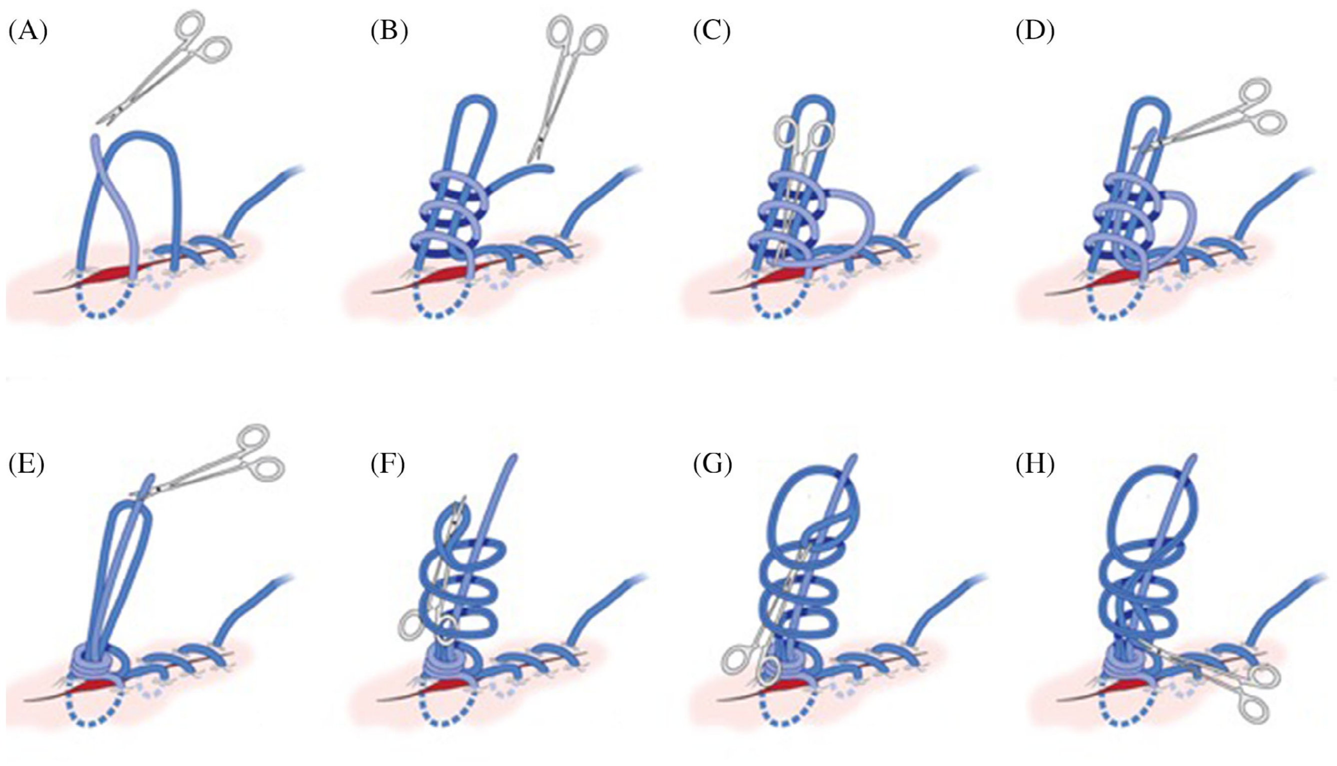

FIGURE 1 Formation of the forwarder end knot. The last bite is taken through the tissue in the continuous suture line to form a loop (A). The free end is wrapped around the loop (B), pulled through the throws (C,D), and then tightened (E). To cross-lock the knot, the loop is wrapped around the needle holders to form throws (F), pulled through the throws (G,H), and finally tightened

Five knots of the 10 knots in each group were randomly selected, and knot height and diameter were measured by using digital images from a microscope with a micrometer (Olympus SZX7; Olympus Corporation of the Americas, Center Valley, Pennsylvania) to the resolution of 0.01 mm. Knot height and diameter were used to calculate approximate knot volume by using the formula $V = \pi r^2 h$.[13] An additional five knots of each type were tied, with all tag ends cut to 3 mm. These knots were weighed to the closest 0.1 mg by using an electronic scale (Mettler AE 163; Mettler Direct, San Diego, California).

Knot distraction was performed by using a universal testing machine (Series 5565; Instron). Each knot was individually loaded onto the bar, which represented the last bite of tissue. The free end of the suture that would form the continuous suture line was held by the upper clamp at an initial distance of 10 cm and put under a preload of 21 N to eliminate slack. The upper clamp was then distracted at a rate of 20 mm/minute until the knot failed due to unraveling, slipping, or breaking of the suture. Mode of knot failure (knot unraveling, knot slippage, or suture breakage) was determined by using a camera (Casio Exilim; Casio America, Dover, New Jersey) that recorded at 60 frames/second mounted on the Instron 5565 universal testing machine. Knot slippage greater than 3 mm, due to the cut tag ends, would result in the knot unraveling.

Testing machine software (Bluehill 2.24.787; Instron) was used to detect the KHC, which is defined as the maximum force that can be applied before knot failure. This was recorded for each suture and used to calculate RKS on the basis of the suture material's tensile strength by using the formula $RKS\% = [KHC/TS] \times 100$.[11]

Statistical analysis was performed in Excel (Microsoft, Redmond, Washington) to collate the data, followed by analysis in XLSTAT (Addinsoft, New York, New York) and SAS 9.3 (SAS Institute, Cary North Carolina). Anderson Darling tests were performed to ensure normality. Data were analyzed by using the general linear model for analysis of variance and Scheffe's test for multiple comparisons. Differences in KHC, RKS, knot volume, and knot weight between knot type, number of throws, and suture material were assessed via Bonferroni's post hoc analysis. Statistical significance was defined as $P < .05$.

3 | RESULTS

3.1 | Knot holding capacity and RKS

When we compared FE knots tied in different suture materials, the FE knots tied in 3 USP polyglactin 910 had higher KHC compared with FE knots in both 2 USP polydioxanone and 2 USP polyglactin 910 ($P < .001$). Forwarder end knots tied in 2 USP polyglactin 910 also had higher KHC compared with 2 USP polydioxanone ($P < .001$). No difference in RKS was seen between FE knots tied in different suture materials ($P > .16$).

The FE knots tied with 2 USP polydioxanone in all numbers of throws had 80% (1.8 fold) higher KHC and RKS values compared with all SQ and SU knots ($P < .001$) and 10% (1.1 fold) higher KHC and RKS values compared with AB knots (KHC, $P = .041$; RKS, $P = .042$; Figure 2). The FE knots tied in 2 USP polyglactin 910 in all number of throws had 20% (1.2 fold) higher KHC and RKS compared with all SQ and SU knots ($P < .001$) but were not different compared with AB knots (KHC, $P = .830$; RKS, $P = .823$). Forwarder end knots tied in 3 USP polyglactin 910 in all number of throws had 23% (1.2 fold) higher KHC and RKS compared with all SQ and SU knots ($P < .001$), but FE KHC values were not different compared with AB knots (KHC, $P = .080$; RKS, $P = .081$). Overall, when the RKS values were evaluated, FE knots were 28% to 66.99% (1.2-1.6 fold) stronger than SQ and SU knots and 0%–8% (<1.08 fold) weaker than AB knots (Figures 2 and 3).

3.2 | Mode of failure

In all trials, the FE and AB knots failed due to suture breakage at the knot but never unraveled or slipped. In all suture types, percentages of SQ and SU knots ranging from 10% to 100% slipped or unraveled when tied with fewer than seven throws (Table 1).

3.3 | Knot size

The FE knots tied in 2 USP polydioxanone and 2 USP polyglactin 910 in all throws were 22.8% to 56% (1.2-1.6 fold) smaller than those tied in 3 USP polyglactin 910 ($P < .003$); however, there was no difference between the size of the knots tied with 2 USP polydioxanone and those tied with 2 USP polyglactin 910 ($P = .487$).

Forwarder end knots tied with 2 USP polyglactin 910 in all number of throws were 40% to 99% (1.4-2.0 fold) larger than AB knots ($P = .001$) and 21.1% to 38.3% (1.2-1.4 fold) smaller than SQ and SU knots ($P < .028$). The FE knots tied in 3 USP polyglactin 910 in all throws were 40% to 90% (1.4-1.9 fold) larger than AB knots ($P < .001$) and 35.7% to 44.4% (1.4 fold) smaller than SQ and SU knots ($P < .009$). Forwarder end knots in 2 USP polydioxanone were not different in size compared with any of the other knot types tested (AB, $P = .266$; SQ, $P = .504$; SU, $P = .363$).

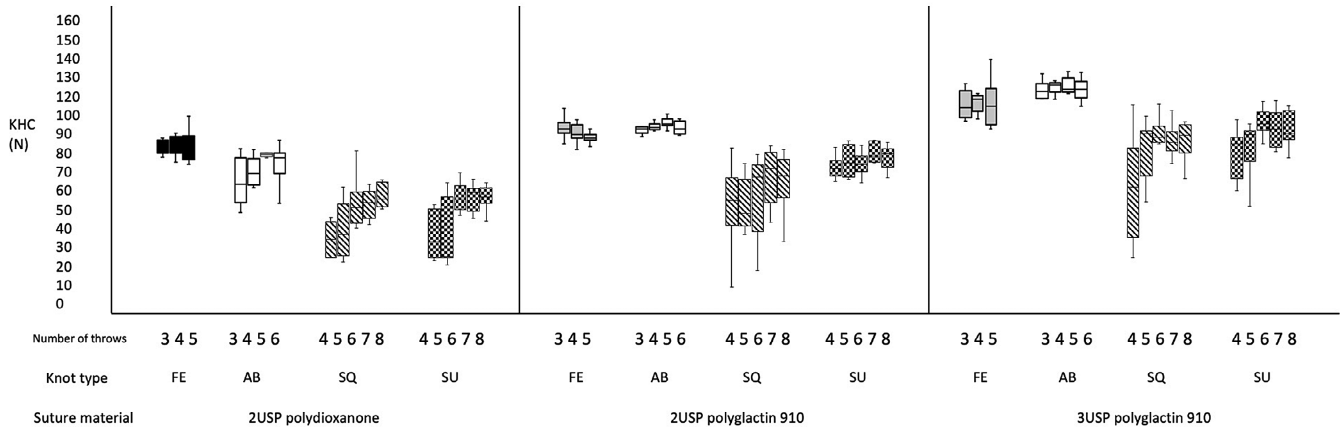

FIGURE 2 Box plots of KHC of each knot type for knots tied with 2 USP polydioxanone, 2 USP polyglactin 910, and 3 USP polyglactin 910. Boxes represent the upper and lower quartiles, whiskers represent the range, and the center line represents the median value. The FE knot (solid) and AB knots (open) had greater KHC values compared with SQ (diagonal lines) and SU (grid lines) knots in all types of suture (*P* < .001). AB, Aberdeen; FE, forwarder end; KHC, knot holding capacity; SQ, square; SU, surgeon's; USP, United States Pharmacopeia

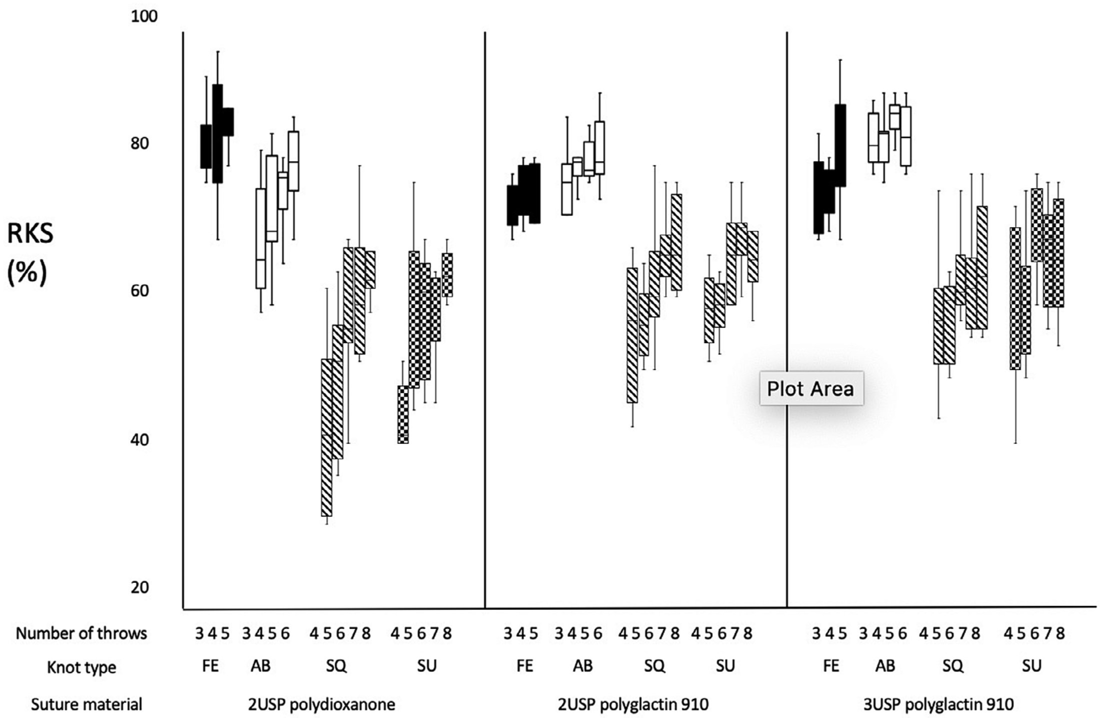

FIGURE 3 Box plots of RKS of each knot type for knots tied with 2 USP polydioxanone, 2 USP polyglactin 910, and 3 USP polyglactin 910. Boxes represent the upper and lower quartiles, whiskers represent the range, and the center line represents the median value. The FE knot (solid) and AB knots (open) had greater RKS values compared with SQ (diagonal lines) and SU (grid lines) knots in all types of suture (*P* < .001). AB, Aberdeen; FE, forwarder end; RKS, relative knot security; SQ, square; SU, surgeon's; USP, United States Pharmacopeia

3.4 | Knot weight

The FE knots tied with 2 USP polyglactin 910 were 21.2% to 41.0% (1.2-1.4 fold) lighter than those in 2 USP polydioxanone (*P* < .001). Knots tied in 3 polyglactin 910 were 22.2% to 34.2% (1.3 fold) heavier than those tied in 2 USP polyglactin 910 (*P* < .001). All FE knots in all types of suture were 13.1% to 47.0% (1.1-1.5 fold) heavier than all other knot types in the same suture material (*P* < .001; Figure 4).

4 | DISCUSSION

The main finding of this study was that the FE knot had a larger KHC and RKS compared with SQ and SU knots

TABLE 1 Percentage of each type of knot that unraveled or slipped during testing

Throws, n	Knot type											
	2 USP polydioxanone, %				2 USP polyglactin 910, %				3 USP polyglactin 910, %			
	FE	AB	SQ	SU	FE	AB	SQ	SU	FE	AB	SQ	SU
3	0	0			0	0			0	0		
4	0	0	100[a]	40	0	0	90[a]	80[b]	0	0	100[a]	100[a]
5	0	0	60[c]	20	0	0	100[a]	60[c]	0	0	80[b]	70[d]
6		0	10	10		0	60[c]	0		0	60[c]	20
7			10	0			0	0			0	0
8			0	0			0	0		...	0	0

Abbreviations: ..., not applicable; AB, Aberdeen; FE, forwarder end; SQ, square; SU, surgeon's; USP, United States Pharmacopeia.
[a]$P < .0001$, differences between SQ/SU compared with FE/AB knots, where FE/AB knots are less likely to slip.
[b]$P = .001$, differences between SQ/SU compared with FE/AB knots, where FE/AB knots are less likely to slip.
[c]$P = .0011$, differences between SQ/SU compared with FE/AB knots, where FE/AB knots are less likely to slip.
[d]$P = .003$, differences between SQ/SU compared with FE/AB knots, where FE/AB knots are less likely to slip.

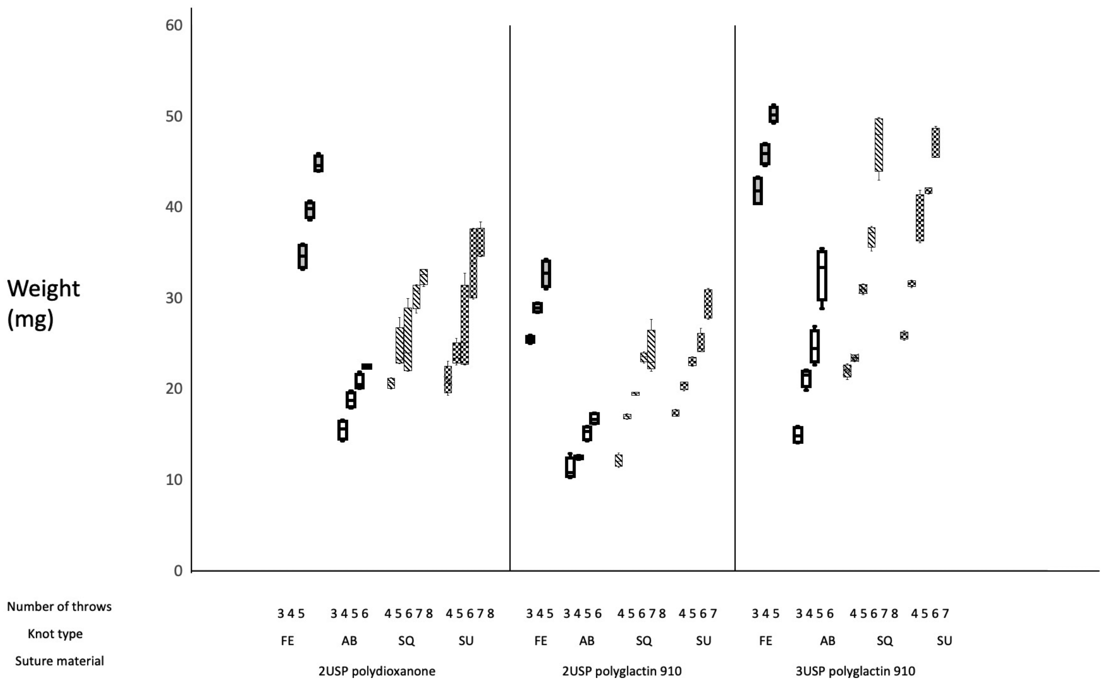

FIGURE 4 Box plots of the weight of each knot type for knots tied with 2 USP polydioxanone, 2 USP polyglactin 910, and 3 USP polyglactin 910. Boxes represent the upper and lower quartiles, whiskers represent the range, and the center line represents the median value. The FE knot (solid) had greater weight compared with AB knots (open), SQ (diagonal lines), and SU (grid lines) knots in all types of suture ($P < .001$). AB, Aberdeen; FE, forwarder end; SQ, square; SU, surgeon's; USP, United States Pharmacopeia

but not compared with AB knots tied in polyglactin 910. Forwarder end knots tied in polydioxanone had a higher KHC and RKS compared with AB knots. The FE and AB knots had increased knot security compared with SQ and SU knots. Aberdeen knots had the smallest volume, and SQ and SU knots had the largest volume. Aberdeen knots had the lowest weight, and FE knots had the highest weight. The knot with the highest KHC and lowest volume and weight was the AB knot with four throws and one turn in 3 USP polyglactin 910. The FE knot with the highest KHC and lowest volume and weight had three throws in each direction in 3 USP polyglactin 910.

In this study, the FE knot had a larger KHC and RKS compared with SQ and SU knots, regardless of the number of throws. These results for forwarder termination knots are similar to those found for forwarder initiation knots,[11] and provide evidence that the FE knot has greater strength compared with both the SQ and SU knots in vitro. All of the FE knots and AB knots failed by suture breakage at the knot rather than slipping or unraveling, which provides evidence that both knot types are, by definition, secure knots.[14] However, the FE knot in polyglactin 910, was weaker than the AB knot. This could be due to the fact that AB knots self-tighten and introduce slack into the suture line[10] during distraction on the materials testing machine, which could result in an apparently higher KHC as translation occurs prior to suture breakage. In comparison, as both the working and the standing end of the suture are locking in place, the FE knot does not allow for slack to be introduced into continuous suture line, which could result in more strain being placed on the knot at lower levels of tension, thereby resulting in the slightly lower KHC when compared with the AB knot. Measurement of the amount of displacement of the AB knot has not been performed and was not pursued in this study.

The FE knot was found to be smaller than SQ and SU knots in polyglactin 910. However, FE knots were larger than AB knots in polyglactin 910. The fact that the FE knot is smaller than SQ and SU knots could provide a benefit in reducing the incidence of local tissue reaction, suture extrusion, and sinus tract formation.[15] Therefore, the FE knot may be preferable to SQ and SU knots for these reasons. The authors suggest that self-locking knots may be smaller than SQ and SU knots because it is easier to create a tight knot with the FE knot because the throws are tightened at the same time, negating the requirement to tighten each throw individually and potentially losing knot conformation due to the suture memory.

Other researchers have used knot weight in conjunction with knot volume as an indicator of overall knot size.[9,11,16] Knot weight provides a better indication of how much suture is contained within the knot, rather than limiting the measurements to those that can be gained with two-dimensional analysis. In this study, the FE knot was heavier than all other knots tested. This differs from the knot volume results, in which the FE knot was smaller than SQ and SU knots when tied in 2 and 3 USP polyglactin 910. It is possible that this was because the observation that the throws of the FE knot often override as they are wound in the same plane and direction to form a more cylindrical knot, while the throws of the SQ and SU knots stack in a more rectangular shape. Because surface area may indicate the amount of suture available for reaction in the tissues, the FE knot could reduce tissue reactivity and formation of adhesions despite the increase in mass of suture material placed.[17] in vivo studies are required to assess the clinical relevance of this difference.

In this study, the optimal FE knot was tied with three throws in 2 USP polyglactin 910 because it maximizes strength but minimizes knot volume and weight. According to our ranking system, in 3 USP polyglactin 910, the optimal knot was the AB knot comprising four throws and one turn; the optimal FE knot with 3 USP polyglactin 910 had three throws in each direction in the same suture material. When we consider the recommendation that the minimum number of throws used should be sufficient to maintain knot security but not excessive to minimize foreign material in the surgical site,[8] we believe that the FE knot, which is both smaller and stronger than the SU knot in vitro, may be a viable option in place of using an SU knot when the tissue is under tension.

It has previously been reported that placement of the AB knot can introduce slack in the suture line due to the difficulties of placing it under tension.[10] The FE knot was designed to overcome these difficulties. From the results obtained with the knots in this study, the authors can report that, unlike the AB knot, the FE knot can be placed under tension because the throws and, therefore, any slack in the suture line can be adjusted when the knot is tightened. Because loop security (the ability to maintain a tight suture loop as the knot is tied) is essential to maintaining effective tissue apposition,[18,19] the FE allows for adjustment of loop security after knot formation and could provide an advantage when a celiotomy incision is secured when abdominal closures can be tight.

While this study provides promising new information regarding the biomechanical properties of the FE knot, it does have limitations. First, all tests were performed on dry suture. In previous studies, additional throws were sometimes required to maintain appropriate knot security of the AB knot when 2-0 polydioxanone suture was exposed to fat.[13] To confirm the strength of the FE knot seen in this study, evaluation should be performed on knots tied with large-gauge polydioxanone and polyglactin 910 after exposure to biological substances such as fat and plasma. Second, this study was conducted in a single cycle load-to-failure method under uniform, linear tension. Additional studies in which the load varies and cyclic loading is used would be beneficial to confirm FE knot security under conditions that more closely mimic the forces in vivo. Finally, the knots were not tied in a random order. The SQ and SU knots were tied prior to the AB and FE knots, and it is possible that factors such as fatigue or improvement with practice may play a role.

In summary, the FE knot had higher KHC and RKS compared with both the SQ knot and the SU knot but did improve the security of AB knots in all knot types. The

FE knot was also found, in most cases, to be larger and heavier than most other knot types. However, just as with the AB knot, the FE knot was found to be a secure knot that did not slip when subjected to linear tension. Subjectively, the authors found that the FE knot was easy to place. Additional ex vivo and in vivo testing should be pursued prior to clinical application of the FE knot.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest related to this report.

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