

Research Article

Position Of The Double Throw And Knot Slippage Across Throw Counts: A Benchtop Study Of 960 Knots In Four 3-0 Suture Materials.

Claes Hannibal Kiilerich¹, Gustav Askaner², Frederik Penzien Wainer Mamsen³

¹Department of Plastic Surgery, Aarhus University Hospital, Denmark.

²Caolin Clinic, Denmark.

³Zealand University Hospital, Denmark.

Abstract

Introduction: Surgical knots fail in one of two ways: the knot slips, or the suture ruptures at the knot. Only the second is captured by the knot-pull tensile strength manufacturers report. Yet slippage determines how many throws a surgeon must tie, and the knot tied may itself affect the load at which the suture ruptures. The surgeon's knot places a double throw first, to hold tissue apposition while the second throw is placed. Whether it also contributes to final security, and more so when placed second, has not been examined across throw counts with failure mode as the outcome.

Materials and methods: Four 3-0 sutures were tested: Dafilon and Monosof (polyamide monofilament, non-absorbable), Monosyn (glyconate monofilament, absorbable) and Novosyn (polyglactin 910 braided, absorbable). Four configurations were tested at throw counts from two to five: square (1=1), surgeon's (2=1), reversed surgeon's (1=2) and double-double (2=2), with 15 knots at every combination. Knotted loops were tied wet by hand over a mandrel, tails cut to 3 mm, and pulled to failure at 150 mm/min. The primary outcome was failure mode, slippage or rupture. The secondary outcome was the load carried by the loop at rupture, analysed only where at least 14 of 15 specimens ruptured. Analysis used Firth-penalised logistic regression and rank-based comparisons.

Results: 960 knots were analysed. Throw count dominated slippage across the whole range tested, from two to five (adjusted odds ratio (OR) 0.017 per additional throw, 95% confidence interval (CI) 0.009 to 0.030, $p < 0.001$); slippage fell from 222 of 240 knots at two throws to 161 of 240 at three, 46 of 240 at four and 1 of 240 at five, each step significant ($p < 0.001$). Configuration mattered almost entirely at three and four throws. The reversed surgeon's knot, which carries the same turns as the surgeon's knot and is therefore the comparison that isolates the position of the double throw, slipped less (OR 0.25, 95% CI 0.12 to 0.52, $p < 0.001$). The square knot and the double-double differ from the surgeon's knot in bulk as well as arrangement, and their estimates reversed according to whether the model adjusted for throws or turns, so both are reported. The configuration effect was material-specific: present in both polyamides, present for the double-double in the braided material, and absent in the glyconate monofilament, where the surgeon's knot was as secure as any configuration tested. Throws needed for at most one slip in 15 ranged from three (Novosyn) to five (Monosyn). Loop rupture load ranged from 32.2 N (Dafilon) to 57.2 N (Monosyn); per strand, all exceeded the United States Pharmacopeia knot-pull minimum by 1.4 to 2.2 times.

Conclusions: In this benchtop model a double throw placed second reduced slippage at the throw counts where knots are otherwise marginal, in both polyamides at matched knot bulk and in the braided material for the double-double. Five throws gave no slippage in any configuration or material except one knot in 15 in the Monosyn surgeon's knot, while three throws sufficed in the braided material and four in the polyamides. Because tightening force was not instrumented, and the surgeon's knot's first throw serves to hold apposition under tension, which a mandrel does not test, these are mechanical findings that require confirmation in tissue with instrumented tension before they should change practice.

Keywords: surgical knot security, suture materials, knot slippage, surgeon's knot, biomechanical testing, polyglactin 910, monofilament suture, tensile strength.

***Corresponding Author:** Claes Hannibal Kiilerich. Department of Plastic Surgery, Zealand University Hospital, Region Zealand, Roskilde, Denmark. Email: clae0118@gmail.com.

Received: 24-September-2026, Manuscript No. AIPS - 6205 ; **Editor Assigned:** 25-September-2026 ; **Reviewed:** 09-October-2026, QC No. AIPS - 6205 ;

Published: 26-October-2026. **DOI:** 10.52338/aips.2026.6205.

Citation: Claes Hannibal Kiilerich. Position Of The Double Throw And Knot Slippage Across Throw Counts: A Benchtop Study Of 960 Knots In Four 3-0 Suture Materials. Advances in Plastic Surgery. 2026 October; 19(1). doi: 10.52338/aips.2026.6205.

Copyright © 2026 Claes Hannibal Kiilerich. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

INTRODUCTION

A surgical knot has two ways of giving way. Either the throws slide over one another and the loop opens, or the throws hold and the suture itself ruptures, almost always at the knot, where the strand has been bent most sharply. Thacker et al. formalised this distinction half a century ago [1]. The two modes are not interchangeable: rupture occurs at a load that is a property of the material and is reported by the manufacturer, while slippage occurs at a load that may be a small fraction of it and is a property of how the knot was tied [2,3]. Trimbos measured that fraction directly, finding loop-holding capacities of 5% to 65% of the strand's tensile strength [4].

Regulatory specification reflects only the first of these. For size 3-0 the United States Pharmacopeia (USP) specifies a minimum average knot-pull tensile strength and nothing else [5,6], and Holmlund observed in 1976 that strength and diameter are "the only physical data that are used to specify surgical suture materials," while "knot properties are of great interest to the surgeon" [7]. The number of throws needed to make a knot hold, which is the decision a surgeon actually makes at the operating table, is nowhere specified.

That decision carries costs on both sides. What tissue reacts to is knot bulk rather than throw count as such: van Rijssel et al. found that adding throws raised knot volume about one and a half times and tissue reaction by up to 1.9 times [8]. Each additional throw also takes time, and with absorbable sutures the aim is to leave as little polymer in the patient as possible. Against that, a knot that slips has failed completely, at a load well below what the material could have carried.

The evidence on the throw count required is substantial but not uniform. Two recent systematic reviews agree that configuration, material, size and throw count all govern security, and that square and surgeon's knots generally need three to five throws with a 3 mm tail [3,9]. The specific numbers depend on the material: Zimmer et al. recommended four throws for monofilament nylon and five for multifilament nylon [10], and Batra et al. found four-throw square knots secure while showing that the individual surgeon's technique materially changed the result [11]. Tidwell et al., testing Monosof among other materials, recommended at least five flat throws for most of their panel [12].

Construction matters as much as count. In sliding knots the benefit of additional throws is significant only in monofilament [13]. In one series all nylon specimens failed by slippage while every absorbable suture broke before the knot came undone [2], and monofilament polyamide is less stiff than braided material, though friction and flexural rigidity bear most directly on slippage [7]. Monofilament knots tied by experienced surgeons, salvaged and examined microscopically, had assumed a sliding conformation in vivo

whatever the surgeon intended [14].

The configuration question is less settled. The surgeon's knot, whose first throw carries two turns, exists to hold tissue apposition under tension while the second throw is placed. Whether that double throw also secures the completed knot is a separate question, and the published evidence suggests it does not: Muffly et al. found no difference from a square knot in tensile strength or in the proportion that untied [15], and Brouwers et al., loading knots dynamically, classed the two-throw surgeon's and square knots together as predominantly slipping [16]. Lee et al., in 2,160 knots, found that a single-hitch first throw cut breaking force by up to 40% [17]. Two mechanisms have been proposed: that the friction gained from a double throw is offset by the more acute angulation it forces on the strand, or that a double first throw resists seating as much as it resists loosening; Johanns et al. have shown that pre-tension, throw count and friction enter a single relationship governing knot strength [18]. On either account the position of the double throw ought to matter, and Dinsmore concluded that knots whose second throw carries two turns are the most efficient [19].

The reversed surgeon's knot, a single throw followed by a double, has been tested three times. Abellán et al. included a 1=2=1 configuration among three tested in five 5-0 materials and found a significant configuration effect [20]; Erten Taysi et al. and Taysi et al. tested it in non-absorbable monofilaments, the later series in 4-0 at a fixed five throws, finding that it performed poorly on failure load after immersion [21,22]. All used failure load as the outcome with throw count held fixed, and tied the double throw unsquared where the direction is reported. None examined the configuration across throw counts, and none used failure mode as the primary outcome. That gap is the one Wong and McGrouther identified as the field's unmet need: resistance to slippage understood as distinct from resistance to rupture [9]. Failure mode is the outcome that answers the surgeon's question, because a knot that slips at 10 N has failed whatever the material's rated strength.

We therefore tested four knot configurations at two, three, four and five throws in four 3-0 suture materials, asking two questions. First, how many throws does each material and configuration need before knots stop slipping? Second, among knots that do hold, does the configuration change the load the construct carries?

MATERIALS AND METHODS

Suture materials

Four commercially available 3-0 sutures were selected to span the two axes of construction and degradation (**Table 1**). Dafilon (B. Braun, Melsungen, Germany) and Monosof (Medtronic, Minneapolis, MN, USA) are polyamide monofilaments, non-

absorbable, and differ in manufacturer and polyamide grade. Monosyn (B. Braun) is a glyconate monofilament and absorbable. Novosyn (B. Braun) is a coated braided polyglactin 910 and absorbable. All materials were taken from sealed manufacturer packaging and used within a few hours of opening. Absorbable materials were handled with gloves throughout and exposed to as little mechanical and chemical trauma as possible before testing, to avoid pre-test hydrolysis or surface damage. Suture lot numbers were not recorded.

Table 1. Suture materials tested.

Suture	Manufacturer	Polymer	Construction	Degradation	Colour	USP size
Dafilon	B. Braun	Polyamide 6/6.6	Monofilament	Non-absorbable	Blue	3-0
Monosof	Medtronic	Polyamide 6	Monofilament	Non-absorbable	Blue	3-0
Monosyn	B. Braun	Glyconate	Monofilament	Absorbable	Violet	3-0
Novosyn	B. Braun	Polyglactin 910	Braided	Absorbable	Violet	3-0

USP: *United States Pharmacopeia*.

Knot configurations and notation

The notation standardised by Dinsmore is used: throws are written as a sequence in which each digit is the number of turns in that throw, and successive throws are tied in opposite directions so that each is squared on the one before; thus 2=1=1 denotes a first throw of two turns followed by two single-turn throws [19]. All knots were flat knots tied with symmetric tension on the two strands. Four configurations were tested, each escalated from two to five throws. The square knot series comprised 1=1, 1=1=1, 1=1=1=1 and 1=1=1=1=1. The surgeon's knot series comprised 2=1, 2=1=1, 2=1=1=1 and 2=1=1=1=1. The reversed surgeon's knot series comprised 1=2, 1=2=1, 1=2=1=1 and 1=2=1=1=1. The double-double series comprised 2=2, 2=2=1, 2=2=1=1 and 2=2=1=1=1. Fifteen knots were tied in every combination of material, configuration and throw count, giving a complete factorial of 64 combinations and 960 knots.

The four configurations do not carry the same amount of suture at a given throw count, and this bears directly on how they may be compared. At every throw count the square knot carries one turn fewer than the surgeon's knot, the reversed surgeon's knot carries the same number, and the double-double carries one more: at two throws the counts are two, three, three and four turns respectively, rising by one turn for each additional throw. Only the reversed surgeon's knot and the surgeon's knot are matched on turns as well as on throws, so only that pair isolates the position of the double throw from the amount of suture in the knot. The other two comparisons confound arrangement with bulk.

Knot tying

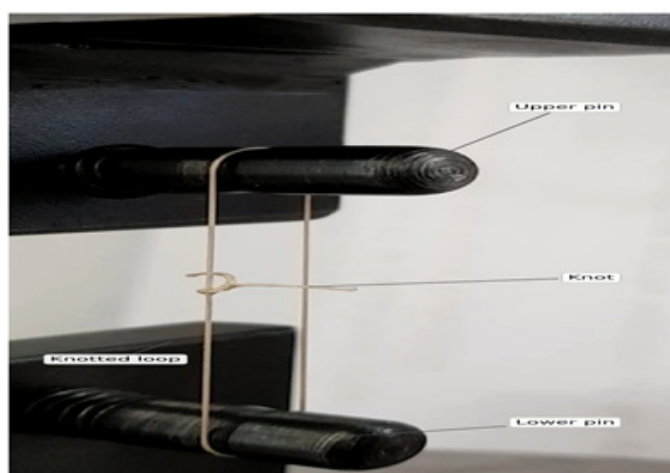
Knots were tied by hand around a metal mandrel of 1.5 cm to 2.5 cm diameter wrapped in gauze soaked in Ringer's solution, giving a knotted loop of roughly 5 cm to 8 cm

circumference. The wrapped mandrel made the knots easier to tie consistently, kept them wet during tying, and allowed the loop to be removed without the mandrel scoring the strand. Knots were wetted in Ringer's solution. After tightening, tails were cut to 3 mm [3], with each cut guided by a measuring rod so that tail length was consistent across all specimens. All knots were tied by a single investigator, which removes variation between operators but makes the results specific to one person's technique; tying technique is itself a known determinant of security [11]. Because the mandrel is rigid, the first throw was never required to hold apposition against tissue recoil while the second throw was placed, so the study does not test the intraoperative function for which the surgeon's knot's double first throw is taught.

Mechanical testing

Knotted loops were mounted over two cylindrical pins in a universal materials testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany) and loaded in tension to failure at a crosshead speed of 150 mm/min at room temperature (**Figure 1**); ambient temperature and humidity were not recorded, and the pin diameter and separation were not measured. Because the specimen is a closed loop, the force recorded by the load cell is shared between two strands, and the tension at the knot is approximately half the recorded load. All forces in this report are loads on the loop unless stated otherwise. Force and elongation were recorded continuously, and for each specimen the machine exported maximum force (F_{max}), elongation at F_{max}, force at break and elongation at break.

Figure 1. Test setup. A knotted 3-0 loop hung over the two pins of the testing machine before loading. The load cell force is shared between two strands, so tension at the knot is about half the value reported.



Outcomes

The primary outcome was failure mode, recorded by direct observation at the moment of failure by the operator conducting the test, and classified as knot slippage, in which the throws slid and the loop opened, or suture rupture, in which the knot held and the strand broke. The site of rupture was recorded in every specimen. The observer was not blinded.

The secondary outcome was the load carried by the loop at rupture, here termed knot-breaking load. Because F_{max} in a specimen that slips is the force at which slippage occurred, not a breaking force, the two are not comparable and were not pooled. Knot-breaking load was therefore analysed only within configurations in which at least 14 of 15 specimens failed by rupture.

Of the 960 knots analysed, 958 produced a mechanical export; two knots in the Monosyn surgeon's knot series loosened before loading and were scored as slippage without a usable export, and one further specimen in that series has a maximum force but no break record, so the analysed dataset holds 957 complete records. Every material, configuration and throw-count combination contributed exactly 15 scored knots.

Statistical analysis

Slippage proportions are reported as counts with percentages. The odds of slippage were modelled by Firth-penalised logistic regression, which stays finite under separation, with the surgeon's knot and Dafilon as references. Four models were fitted: throw count continuous, throw count categorical, total turns in place of throw count, and the first

within each material. Wald 95% confidence intervals and two-sided p values are reported. Matched comparisons with the surgeon's knot, within material and throw count, used Fisher's exact test; no adjustment for multiplicity was made, so these are descriptive. Knot-breaking load is given as median and interquartile range (IQR) and compared by Kruskal-Wallis and Mann-Whitney U tests. No sample-size calculation was performed; 15 knots per combination follows the prior literature. Two-sided $p < 0.05$ was significant. Analysis used Python 3.11 (Python Software Foundation, Wilmington, DE, USA).

Ethics

This study used commercially manufactured suture materials on a benchtop testing apparatus. No human participants, human tissue or animals were involved, and no ethical approval was required.

RESULTS

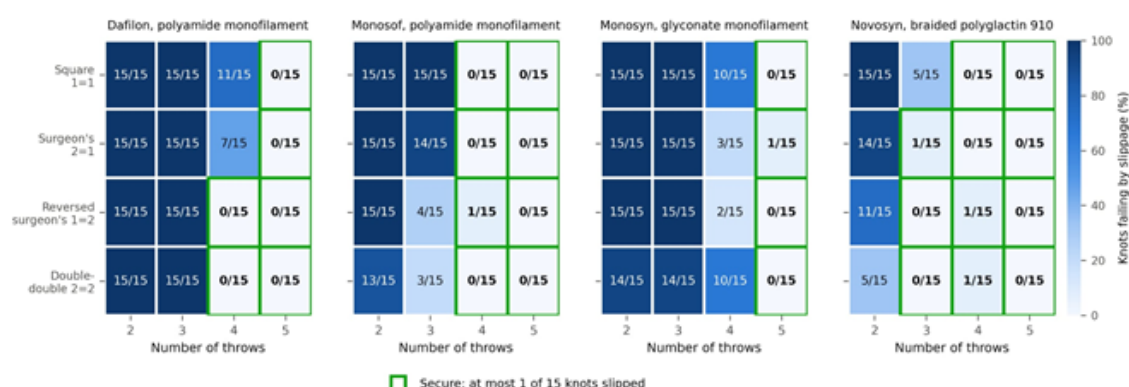
Slippage as a function of throw count

Across 960 knots, failure mode varied systematically with throw count, knot configuration and material (**Table 2, Figure 2**). At two throws, slippage was near-universal in the monofilament materials: 15 of 15 in every Dafilon configuration, in three of four Monosyn configurations and in three of four Monosof configurations. Novosyn behaved differently from the outset, with the double-double configuration slipping in only 5 of 15 knots at two throws.

Table 2. Knots failing by slippage, n/15 (%).

Suture	Knot configuration	2 throws	3 throws	4 throws	5 throws
Dafilon	Square (1=1)	15/15 (100%)	15/15 (100%)	11/15 (73%)	0/15 (0%)
Dafilon	Surgeon's (2=1)	15/15 (100%)	15/15 (100%)	7/15 (47%)	0/15 (0%)
Dafilon	Reversed surgeon's (1=2)	15/15 (100%)	15/15 (100%)	0/15 (0%)	0/15 (0%)
Dafilon	Double-double (2=2)	15/15 (100%)	15/15 (100%)	0/15 (0%)	0/15 (0%)
Monosof	Square (1=1)	15/15 (100%)	15/15 (100%)	0/15 (0%)	0/15 (0%)
Monosof	Surgeon's (2=1)	15/15 (100%)	14/15 (93%)	0/15 (0%)	0/15 (0%)
Monosof	Reversed surgeon's (1=2)	15/15 (100%)	4/15 (27%)	1/15 (7%)	0/15 (0%)
Monosof	Double-double (2=2)	13/15 (87%)	3/15 (20%)	0/15 (0%)	0/15 (0%)
Monosyn	Square (1=1)	15/15 (100%)	15/15 (100%)	10/15 (67%)	0/15 (0%)
Monosyn	Surgeon's (2=1)	15/15 (100%)	15/15 (100%)	3/15 (20%)	1/15 (7%)
Monosyn	Reversed surgeon's (1=2)	15/15 (100%)	15/15 (100%)	2/15 (13%)	0/15 (0%)
Monosyn	Double-double (2=2)	14/15 (93%)	14/15 (93%)	10/15 (67%)	0/15 (0%)
Novosyn	Square (1=1)	15/15 (100%)	5/15 (33%)	0/15 (0%)	0/15 (0%)
Novosyn	Surgeon's (2=1)	14/15 (93%)	1/15 (7%)	0/15 (0%)	0/15 (0%)
Novosyn	Reversed surgeon's (1=2)	11/15 (73%)	0/15 (0%)	1/15 (7%)	0/15 (0%)
Novosyn	Double-double (2=2)	5/15 (33%)	0/15 (0%)	1/15 (7%)	0/15 (0%)

All 64 combinations of material, configuration and throw count contributed 15 knots. With 15 knots per combination, an observed 0/15 has a 95% Clopper-Pearson upper bound of 21.8% and an observed 15/15 a lower bound of 78.2%.

Figure 2. Knots failing by slippage. Each cell is one combination of material, configuration and throw count and contains 15 knots; the printed value and the shading are the number and the percentage that slipped. Green outlines mark cells in which at most one knot in 15 slipped.

Adding throws reduced slippage across the whole range tested. Pooled across materials and configurations, 222 of 240 knots slipped at two throws (92.5%), 161 of 240 at three (67.1%), 46 of 240 at four (19.2%) and 1 of 240 at five (0.4%). In the Firth-penalised model each additional throw carried an adjusted odds ratio (OR) for slippage of 0.017 (95% confidence interval (CI) 0.009 to 0.030, $p < 0.001$); entered categorically, the odds relative to two throws were 0.035 (95% CI 0.015 to 0.083) at three throws, 0.00036 (95% CI 0.00010 to 0.0013) at four and 0.0000050 (95% CI 0.0000060 to 0.000041) at five, all $p < 0.001$ (**Table 3**).

Table 3. Firth-penalised logistic regression for failure by slippage, under two ways of accounting for knot bulk.

Predictor	Adjusted for throws: OR (95% CI)	p	Adjusted for total turns: OR (95% CI)	p
Square (1=1) vs surgeon's (2=1)	2.95 (1.41 to 6.19)	0.004	0.049 (0.021 to 0.12)	<0.001
Reversed surgeon's (1=2) vs surgeon's (2=1)	0.25 (0.12 to 0.52)	<0.001	0.25 (0.12 to 0.52)	<0.001
Double-double (2=2) vs surgeon's (2=1)	0.19 (0.089 to 0.40)	<0.001	11.4 (5.00 to 25.9)	<0.001
Each additional throw, or turn	0.017 (0.0092 to 0.030)	<0.001	0.017 (0.0092 to 0.030)	<0.001
Monosof vs Dafilon	0.054 (0.023 to 0.12)	<0.001	0.054 (0.023 to 0.12)	<0.001
Monosyn vs Dafilon	1.52 (0.73 to 3.17)	0.26	1.52 (0.73 to 3.17)	0.26
Novosyn vs Dafilon	0.0029 (0.00095 to 0.0089)	<0.001	0.0029 (0.00095 to 0.0089)	<0.001

$n=960$ knots. Reference categories: surgeon's knot and Dafilon. The two models differ only in whether the bulk covariate is the number of throws or the total number of turns; because the reversed surgeon's knot carries the same turns as the surgeon's knot at every throw count, its estimate is identical under both, whereas the square knot (one turn fewer) and the double-double (one turn more) reverse. In a third model with throw count entered categorically rather than continuously, the odds of slippage relative to two throws were 0.035 (95% CI 0.015 to 0.083) at three throws, 0.00036 (95% CI 0.00010 to 0.0013) at four and 0.0000050 (95% CI 0.00000060 to 0.000041) at five, all $p<0.001$. Wald intervals and two-sided p values from the penalised information matrix.

Knot configuration

Configuration had an independent effect, and it operated almost entirely at three and four throws. At two throws almost nothing held and at five throws almost everything did: pooled across materials, the square, surgeon's, reversed surgeon's and double-double configurations slipped in 60, 59, 56 and 47 of 60 knots at two throws, and in 0, 1, 0 and 0 of 60 at five. Between those bounds the ordering was consistent: 50, 45, 34 and 32 of 60 at three throws, and 21, 10, 4 and 11 of 60 at four.

Because the configurations differ in bulk as well as in arrangement, the pooled estimates depend on how bulk is counted, and Table 3 reports them both ways. The reversed surgeon's knot is the exception: it carries the same number of turns as the surgeon's knot at every throw count, so its estimate is identical under either accounting and is the one comparison that isolates the position of the double throw. It slipped less than the surgeon's knot (OR 0.25, 95% CI 0.12 to 0.52, $p<0.001$).

The square knot and the double-double do not have that property, and their estimates reverse according to the choice. Adjusted for throws, the square knot slipped more than the surgeon's knot (OR 2.95, 95% CI 1.41 to 6.19, $p=0.004$) and the double-double less (OR 0.19, 95% CI 0.089 to 0.40, $p<0.001$); adjusted for total turns both reverse, the square knot slipping less (OR 0.049, 95% CI 0.021 to 0.12, $p<0.001$) and the double-double more (OR 11.4, 95% CI 5.0 to 25.9, $p<0.001$).

The pooled estimates also average over differences between materials (Table 4). In Dafilon, both double-throw-second configurations reached zero slippage at four throws while the surgeon's knot slipped in 7 of 15 and the square knot in 11 of 15, giving ORs of 0.027 (95% CI 0.0014 to 0.55, $p=0.019$) for each against the surgeon's knot. In Monosof the reversed surgeon's knot had an OR of 0.085 (95% CI 0.017 to 0.43, $p=0.003$) and the double-double 0.024 (95% CI 0.0037 to 0.16, $p<0.001$). In Novosyn the double-double remained

distinguishable (OR 0.13, 95% CI 0.031 to 0.54, $p=0.005$) while the reversed surgeon's knot did not (OR 0.50, 95% CI 0.13 to 1.93, $p=0.31$). Monosyn ran the other way: neither the reversed surgeon's knot (OR 0.62, 95% CI 0.16 to 2.41, $p=0.49$) nor the double-double (OR 2.38, 95% CI 0.64 to 8.86, $p=0.20$) improved on the surgeon's knot, and at four throws the surgeon's and reversed surgeon's knots were the two most secure, slipping in 3 of 15 and 2 of 15 against 10 of 15 for both the square knot and the double-double.

Adjusted for throws, the square knot slipped more often than the surgeon's knot in all four materials separately, with ORs of 2.91, 1.49, 3.66 and 3.05 in Dafilon, Monosof, Monosyn and Novosyn, but the confidence interval included one in every material ($p=0.17$, 0.65, 0.058 and 0.11), and the direction again depends on whether bulk is counted in throws or in turns. The difference arises at four throws in Dafilon (11 of 15 against 7 of 15) and Monosyn (10 of 15 against 3 of 15) and at three throws in Novosyn (5 of 15 against 1 of 15), while in Monosof the two never differed by more than one knot.

Restricting to combinations directly matched on material and throw count, the reversed surgeon's knot slipped in 94 of 240 knots (39.2%) and the double-double in 90 of 240 (37.5%), compared with 115 of 240 (47.9%) for the surgeon's knot and 131 of 240 (54.6%) for the square knot. Seven of the 48 matched comparisons reached $p<0.05$ by Fisher's exact test. Five favoured a double throw placed second: in Monosof at three throws the reversed surgeon's knot slipped in 4 of 15 and the double-double in 3 of 15 against 14 of 15 for the surgeon's knot ($p=0.0005$ and $p=0.0001$); in Dafilon at four throws both slipped in 0 of 15 against 7 of 15 ($p=0.006$ each); and in Novosyn at two throws the double-double slipped in 5 of 15 against 14 of 15 ($p=0.002$). Two ran the other way, in Monosyn at four throws, where the square knot and the double-double each slipped in 10 of 15 against 3 of 15 for the surgeon's knot ($p=0.025$ each). These are unadjusted across 48 tests and should be read as descriptive.

Table 4. Odds ratios for each configuration relative to the surgeon's knot, within material

Comparison	Dafilon	Monosof	Monosyn	Novosyn
Square (1=1) vs surgeon's (2=1)	2.91 (0.64 to 13.2), p=0.17	1.49 (0.27 to 8.27), p=0.65	3.66 (0.96 to 14.0), p=0.058	3.05 (0.79 to 11.8), p=0.11
Reversed surgeon's (1=2) vs surgeon's (2=1)	0.027 (0.0014 to 0.55), p=0.019	0.085 (0.017 to 0.43), p=0.003	0.62 (0.16 to 2.41), p=0.49	0.50 (0.13 to 1.93), p=0.31
Double-double (2=2) vs surgeon's (2=1)	0.027 (0.0014 to 0.55), p=0.019	0.024 (0.0037 to 0.16), p<0.001	2.38 (0.64 to 8.86), p=0.20	0.13 (0.031 to 0.54), p=0.005

Odds ratios with 95% confidence intervals and two-sided p values from Firth-penalised models fitted within each material, with throw count as a continuous covariate. The square-knot and double-double rows are conditional on bulk being counted in throws; see Table 3.

Throws required for a secure knot

The number of throws at which slippage fell to zero, and to at most one in 15, varied by material and configuration (**Table 5**, **Figure 3**). Novosyn was least demanding, reaching zero at three throws with the reversed surgeon's and double-double configurations and at four with the square and surgeon's knots. Monosof reached zero at four throws in every configuration except the reversed surgeon's knot, which slipped in 1 of 15 at four. Dafilon reached zero at four throws with the two double-throw-second configurations and at five with the others, and Monosyn only at five, its surgeon's knot still slipping in 1 of 15 at that count. Two series break the pattern, each by a single knot: both Novosyn double-throw-second configurations reached zero at three throws and then slipped in 1 of 15 at four. At rates this low a single event is within sampling variation, and the pattern should be read as a plateau rather than a reversal. Given the 21.8% upper confidence bound on an observed 0 of 15, the throw counts in **Table 5** mark where slippage became rare in this laboratory, not a guarantee of zero.

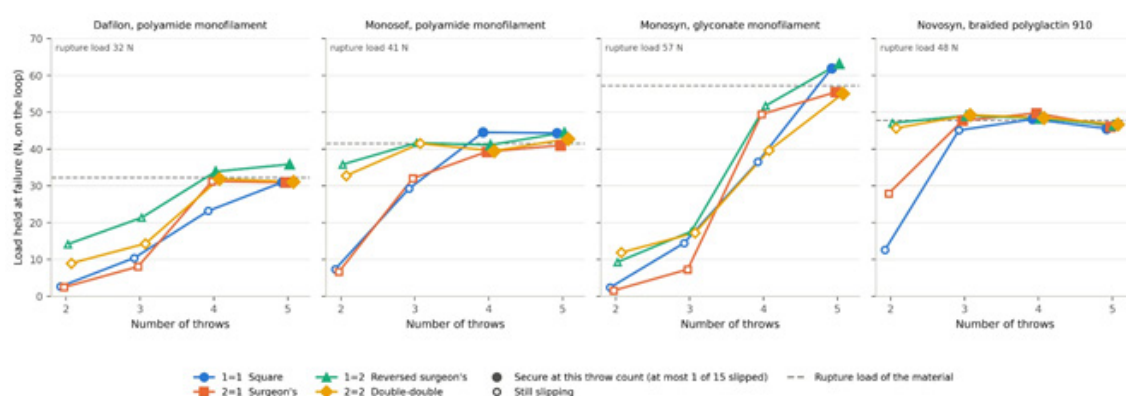
Table 5. Minimum number of throws at which slippage fell to zero, and to at most one in 15.

Suture	Square (1=1)	Surgeon's (2=1)	Reversed surgeon's (1=2)	Double-double (2=2)
Dafilon	5 (5)	5 (5)	4 (4)	4 (4)
Monosof	4 (4)	4 (4)	5 (4)	4 (4)
Monosyn	5 (5)	>5 (5)	5 (5)	5 (5)
Novosyn	4 (4)	4 (3)	3 (3)	3 (3)

Each cell gives the lowest throw count at which no knot slipped, with the lowest throw count at which at most one knot in 15 slipped in parentheses. ">5" indicates that slippage had not reached that threshold at five throws, the highest count tested. An observed 0 of 15 carries a 95% upper confidence bound of 21.8%.

Figure 3 shows the same result as the load the knot actually holds, with each configuration plotted separately. In every material the lines rise with throw count and flatten against the material's rupture load, and the throw count at which a line meets that ceiling is the throw count at which that configuration stops slipping. The configurations do not arrive together. In Dafilon the reversed surgeon's knot and the double-double already hold 33.8 N and 31.8 N at four throws against a rupture load of 32.2 N, while the square knot holds 23.1 N. In Monosof the same two configurations hold 35.8 N and 32.8 N at two throws, where the square and surgeon's knots hold 7.3 N and 6.6 N. In Novosyn they hold 47.0 N and 45.7 N at two throws against a rupture load of 47.8 N, which the square knot does not approach until three. Monosyn is again the exception: no configuration approaches its 57.2 N ceiling before four throws, and at that count the double-double is the second weakest of the four.

Figure 3. Median load at failure against throw count, by configuration. Below the throw count at which a configuration stops slipping the point is a slippage load, at or above it a breaking load. Filled markers indicate at most one slip in 15, open markers continued slipping. The dashed line is the material's rupture load from the rupture-dominant configurations. Markers are dodged horizontally so coincident points stay visible.



Knot-breaking load

Twenty-nine configurations, comprising 435 specimens, met the criterion of at least 14 of 15 failures by rupture (**Table 6**, **Figure 4**). All ruptures occurred at the knot. Median loop load at rupture differed between materials: Monosyn 57.2 N (IQR 52.9 to 63.2, $n=60$), Novosyn 47.8 N (IQR 46.1 to 49.4, $n=165$), Monosof 41.5 N (IQR 38.0 to 44.9, $n=120$) and Dafilon 32.2 N (IQR 30.3 to 34.3, $n=90$); Kruskal-Wallis $H=323.0$, $p<0.001$. Per strand, as the USP knot-pull test is expressed, these are 28.6, 23.9, 20.7 and 16.1 N, exceeding the applicable USP 3-0 minimum of 17.4 N for synthetic absorbable suture by 1.6 and 1.4 times and 9.41 N for Class I non-absorbable suture by 2.2 and 1.7 times [5,6].

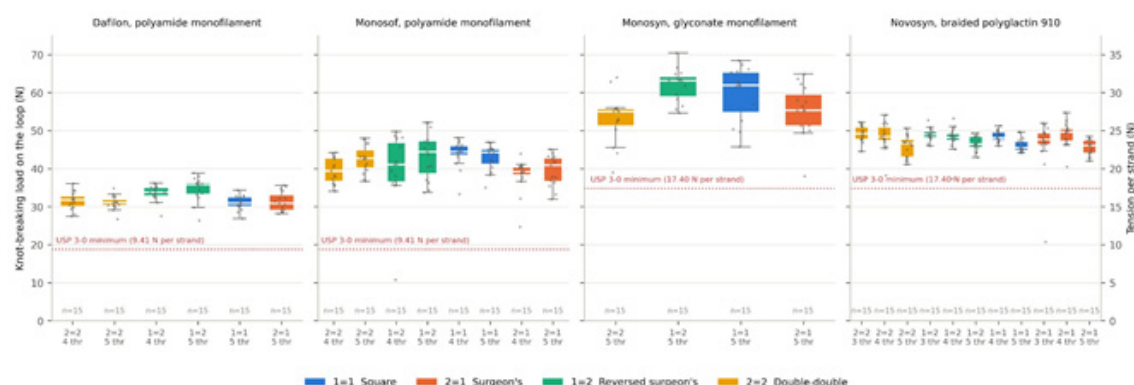
Within materials, configuration had a small and inconsistent effect on the load a holding knot carried, spanning a few newtons and running in opposite directions between materials, against a between-material range of 25 N. Whether the knot held at all was by far the larger effect.

Table 6. Knot-breaking load in rupture-dominant configurations.

Suture	n specimens	Median loop load at rupture (N)	IQR (N)	Per strand (N)	Multiple of USP minimum
Dafilon	90	32.2	30.3 to 34.3	16.1	1.7
Monosof	120	41.5	38.0 to 44.9	20.7	2.2
Monosyn	60	57.2	52.9 to 63.2	28.6	1.6
Novosyn	165	47.8	46.1 to 49.4	23.9	1.4

Restricted to the 29 configurations in which at least 14 of 15 specimens failed by suture rupture. Kruskal-Wallis $H=323.0$, $p<0.001$. IQR: interquartile range; USP: United States Pharmacopeia. Per-strand load is half the loop load. USP 3-0 minimum average knot-pull tensile strength: 17.4 N for synthetic absorbable suture (Monosyn, Novosyn) and 9.41 N for Class I non-absorbable suture (Monosof, Dafilon) [5,6].

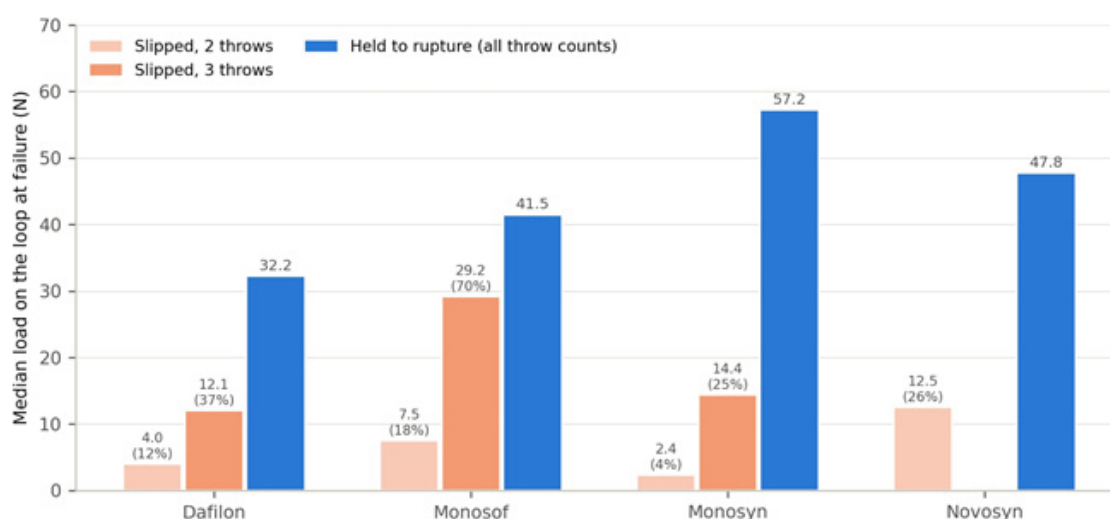
Figure 4. Knot-breaking load by material, configuration and throw count, for every configuration in which at least 14 of 15 specimens ruptured. Boxes show median and interquartile range, whiskers the most extreme values within 1.5 interquartile ranges, individual specimens are overlaid and n is printed beneath each. Left axis, load on the loop; right axis, tension per strand. The dotted line is the applicable United States Pharmacopeia 3-0 minimum knot-pull strength, a per-strand value drawn at twice its nominal level [5,6].



The cost of slippage

The load at which a knot slipped rose with throw count and, at the marginal count, approached the rupture load (**Figure 5**). In series where every knot slipped, the median slippage load as a fraction of the material's median rupture load was 12% at two throws and 37% at three in Dafilon; 18% and 70% in Monosof; 4% and 25% in Monosyn; and 26% at two throws in Novosyn. Pooled across such series it was 9.5 N in Dafilon (29%), 16.7 N in Monosof (40%), 7.9 N in Monosyn (14%) and 12.5 N in Novosyn (26%); all Mann-Whitney comparisons with the holding configurations $p < 0.001$.

Figure 5. Load at failure when the knot slips against the load when it holds. Orange columns give the median slippage load in series where every knot slipped, at two and three throws; the blue column the median rupture load in rupture-dominant configurations. Percentages are the slippage load as a fraction of the rupture load. Values are loads on the loop.



DISCUSSION

Three findings emerge from this study. Throw count was by far the strongest determinant of whether a knot held, and the number required was material-specific rather than universal. A double throw placed second reduced slippage where knots are otherwise marginal: in both polyamides for the turns-matched reversed surgeon's knot, and in the braided material for the double-double. And the two comparisons not made at matched bulk reverse direction according to whether bulk is counted in throws or in turns, which is itself informative.

The position effect is the most secure of the three. The reversed surgeon's knot and the surgeon's knot carry identical turns at every throw count, so the fourfold reduction in the odds of slippage (OR 0.25, 95% CI 0.12 to 0.52, $p < 0.001$) cannot be

attributed to one knot containing more suture than the other. The effect is concentrated where knots are marginal: Dafilon at four throws, where the reversed configuration reached zero while the surgeon's knot slipped in 7 of 15, and Monosyn at three throws, where both double-throw-second configurations slipped in 3 or 4 of 15 against 14 of 15. This is the pattern Dinsmore inferred from the literature to 1995, to which the present study adds the throw-count gradient and failure mode as the outcome [19]. Two mechanisms could produce it and these data cannot separate them: the angulation penalty proposed by Muffy et al. [15], or the simpler possibility that a double first throw resists seating as much as it resists loosening while a double second throw engages its friction against an already-seated base. Johanns et al. have shown that pre-tension enters the knot-strength relationship alongside throw count and friction [18], so either way the effect is conditional on tightening force, which was not instrumented here.

The bulk-dependent comparisons deserve to be stated plainly rather than resolved in whichever direction suits the argument. Counted in throws, the surgeon's knot outperformed the square knot in all four materials, which is not what the published comparisons of those two knots would have predicted [15,16]. Counted in turns, the ordering inverts and the square knot is the more efficient use of a given amount of suture. Both are arithmetically true of the same 960 knots, and the disagreement is a reminder that "which knot is better" is underspecified until one says what is being held constant: the throws-matched reading applies to arranging the next two throws, the turns-matched reading to how much polymer is left behind [8]. We report the square-knot comparison as directional and bulk-dependent, needing independent replication.

Monosyn is the material that refuses the generalisation. In glyconate the reversed surgeon's knot was indistinguishable from the surgeon's knot, and the double-double was no better than the square knot, slipping in 10 of 15 at four throws against 3 of 15 for the surgeon's knot. Glyconate also required the most throws overall and carried the highest breaking load. We found no prior knot-security data on glyconate at any size, and its surface and stiffness were not measured here. A recommendation to place the double throw second is therefore supported in two polyamides and, for the double-double, in coated polyglactin 910, and not in the one glyconate tested.

Our results sit alongside three prior studies of the reversed configuration [20-22], all of which used failure load as the outcome with throw count held fixed, the most recent finding that the configuration performed poorly on failure load after immersion. Those results and ours measure different things: a configuration can carry a lower load once it holds and still be far less likely to slip, and for a surgeon deciding how many

throws to tie the second property governs. Our secondary analysis shows the dissociation directly, configuration moving knot-breaking load by a few newtons against a 25 N range between materials. Lee et al. observed the same asymmetry in 2,160 knots: a single-hitch first throw cut breaking force by up to 40%, yet it was the double-double configuration that slipped most [17].

What these forces mean clinically

A benchtop breaking load is only interesting if it can be set against the loads a closure actually meets, and the comparison is closer than the margins in Table 6 suggest. In healthy adults intra-abdominal pressure rises from a mean of 20 mmHg on standing to 107.6 mmHg on coughing and 171 mmHg on jumping [23]. About 20 kPa, or roughly 150 mmHg, corresponds to a transverse force on the linea alba of about 3.4 N per millimetre of midline [24], of the order of 34 N for every centimetre of wound and so the same order of magnitude as the whole-loop rupture loads measured here, 32 to 57 N. That figure is a force per unit length carried by fascia and suture line together rather than a load on any single knot, but it does show that the margin between what a 3-0 loop can carry and what a cough can generate is narrower than the rated strength alone would suggest.

Direct measurement gives a lower and more reassuring number, and the two should be read together. Höer and Wetter, instrumenting midline sutures in pigs, recorded peaks of 10 to 20 N while the closure was run, falling to about 1 N once the edges were apposed [25]; in a bench model of skin closure, mean maximum pulling forces on the first throw were 3.5 to 8.1 N with individual peaks to 10.7 N [26]. Resting tension in a closed wound is therefore well below the breaking loads reported here, while the transient peaks generated during tying, and plausibly during a cough, are not. It is the peaks that break knots.

Set against that, the effect of knot security is larger than the difference between materials. The 25 N spread in rupture load between Dafilon and Monosyn is real, but a knot that slips forfeits between 60% and 86% of whatever its material could have carried, and more than 95% at two throws in glyconate. A securely tied knot in the weakest material tested holds more than an insecurely tied knot in the strongest, which argues that throw count and configuration deserve at least as much attention as material choice. The precedent is the flexor tendon literature, where repair constructs are selected against measured in vivo tendon forces of 3 N for place-and-hold, 6 N for active finger flexion and 24 N for isolated profundus flexion [27]. No equivalent benchmark exists for knot security and we are not proposing one: no study has linked knot-breaking load to a clinical outcome such as dehiscence or hernia.

Material differences

The material differences were larger than the configuration differences, and one is unexplained. Coated braided polyglactin 910 reached zero slippage at three or four throws, whereas polyamide monofilament needed four or five and glyconate five. This is broadly the pattern of the prior literature: in sliding knots extra throws benefit monofilament far more than multifilament [13], four throws are recommended for monofilament nylon [10], and at least five flat square throws for a panel of materials that included Monosof [12], against which our result of four is one throw fewer. Rodeheaver et al. found uncoated braided polyglactin 910 secure with a two-throw square knot, which we did not reproduce, our two-throw Novosyn square knot slipping in 15 of 15 [28]; the same group later showed that coated polyglactin 910 requires more throws than its uncoated form, and Novosyn is coated, so this is a confirmation rather than a discrepancy [29]. Van Leeuwen and Trimbos, who tested 3-0 Novosyn in sliding-knot configurations, found that 73% of knots slipped and that five throws were significantly stronger than three [30]. The unexplained difference is between the two polyamide monofilaments: Monosof slipped far less than Dafilon (OR 0.054, 95% CI 0.023 to 0.12, $p < 0.001$). They differ in polyamide grade, and may differ in diameter within the USP range, surface finish and stiffness, none measured here. What survives is not that one material is better, but that a single throw-count rule will be simultaneously wasteful in braided absorbables and insufficient in stiff monofilaments. That slipping knots fail at a fraction of the load the material would otherwise carry is why failure mode is the primary outcome here, and the fraction depends on where on the throw-count gradient the knot sits: two-throw monofilament knots gave way at between a twenty-fifth and a fifth of the rupture load, while at three throws in Monosof slipping knots gave way at 70% of it. Pooling slipped and ruptured specimens into a mean failure load therefore mixes two distinct physical events and produces a number that describes neither, which is also why a knot-pull value obtained from a knot tied with enough throws to hold is an incomplete guide [4-7,9]. Adding throws raises knot volume by about half and tissue reaction by up to 1.9 times [8]. At the threshold of at most one slip in 15, the double-throw-second configurations reached security one throw earlier than the surgeon's knot in Dafilon and, for the double-double, one throw earlier in Novosyn. Where a throw is saved it is a real reduction in retained material and time, but neither was measured here and the saving is inferred, not demonstrated.

Limitations

This is a benchtop study and its findings are mechanical. Knots were tied around a gauze-wrapped mandrel of 1.5 cm to 2.5 cm diameter, giving a loop far larger than a dermal

or fascial bite, and were loaded in a single linear pull at a constant rate. Tissue is compliant, loading in vivo is cyclic and multidirectional, and knots are tied under tension against apposed tissue rather than around a rigid former; in particular the first throw was never required to hold apposition while the second was placed, which is the function for which the surgeon's knot exists. Dynamic loading changes the ranking of knots [16], and monofilament knots tied in surgery almost universally assume a sliding conformation regardless of the surgeon's intent [14], so our results characterise the knots as specified rather than what surgeons produce.

Tightening force was applied by hand and not instrumented, so every configuration effect is conditional on the tension used in this laboratory and may narrow in hands that tighten harder. All knots were tied by one investigator, which removes between-operator variation, known to alter security substantially [11], but makes the findings specific to one technique and is the main reason the square-versus-surgeon's comparison needs independent replication.

Two of the three configuration comparisons are confounded by knot bulk. Only the reversed surgeon's knot against the surgeon's knot is matched on turns, and only that comparison supports a claim about the position of the double throw independent of the amount of suture in the knot; the square-knot and double-double estimates are conditional on the accounting chosen.

Failure mode was classified by the operator at the time of testing rather than by an independent blinded assessor. Material was confounded with test session: Dafilon and Monosyn were tested on 3 May 2019 and Monosof and Novosyn between 28 January and 12 February 2020, so every between-material contrast, including the unexplained difference between the two polyamides, carries any difference between the two sessions and any drift in tying habit across them. Only one suture size was tested, and gauge is known to interact with knot security [9]. The panel contains two polyamide monofilaments but only one braided product, so the braided-versus-monofilament contrast rests on a single coated material. These findings require confirmation in tissue, under measured tension, with cyclic loading and blinded assessment of failure mode, before they should change operative practice.

CONCLUSIONS

Across 960 knots in four 3-0 suture materials, the number of throws was the strongest determinant of whether a knot held, and the number required differed by material: three to four throws for coated braided polyglactin 910 (Novosyn), four to five for polyamide monofilament (Dafilon and Monosof), and five for the glyconate monofilament (Monosyn). No single throw-count rule fitted all four.

Knot configuration mattered independently of throw count, but not uniformly, and not independently of knot bulk. The one comparison made at matched bulk, the reversed surgeon's knot against the conventional surgeon's knot, showed that placing the double throw second reduced the odds of slippage roughly fourfold at the throw counts where knots are otherwise marginal, an effect present in both polyamides and absent in the glyconate monofilament, where the surgeon's knot was as secure as any configuration tested. The comparisons involving the square knot and the double-double reverse direction according to whether bulk is counted in throws or in turns, and are reported under both: at a fixed number of throws an extra turn helps, while at a fixed amount of suture the same material resists slippage better distributed over more throws.

Because tightening force was not instrumented and the mandrel does not test the surgeon's knot's intraoperative function of holding apposition, the cautious reading for practice is that throw count, not configuration, is the lever that matters most, and that its setting is material-specific. Against physiological loads these differences are not negligible: the transverse force on a midline wound during a cough is of the same order as the rupture load of a 3-0 loop, and a knot that slips forfeits most of what its material could have carried. These remain mechanical findings from a benchtop model.

Disclosures

Use of artificial intelligence: Artificial intelligence (AI) tools were used to assist with statistical analysis and language improvement during the preparation of this manuscript.

Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare that no financial support was received from any organisation for the submitted work, that they have no financial relationships with any organisation that might have an interest in the submitted work, and that there are no other relationships or activities that could appear to have influenced the submitted work.

REFERENCES

- Thacker JG, Rodeheaver G, Moore JW, Kauzlarich JJ, Kurtz L, Edgerton MT, Edlich RF: Mechanical performance of surgical sutures. *Am J Surg.* 1975, 130:374-380. 10.1016/0002-9610(75)90408-0
- Kim JC, Lee YK, Lim BS, Rhee SH, Yang HC: Comparison of tensile and knot security properties of surgical sutures. *J Mater Sci Mater Med.* 2007, 18:2363-2369. 10.1007/s10856-007-3114-6
- Bushong EE, Janis JE: Knot security 101: a comprehensive practical review to optimal knot configuration, pulling direction, throw count, and tail length. *Plast Reconstr Surg Glob Open.* 2024, 12:e6047. 10.1097/GOX.0000000000006047
- Trimbos JB: Security of various knots commonly used in surgical practice. *Obstet Gynecol.* 1984, 64:274-280.
- Nonabsorbable surgical suture. USP-NF. United States Pharmacopeial Convention, Rockville, MD; 2020. 10.31003/USPNF_M80200_04_01
- Absorbable surgical suture. USP-NF. United States Pharmacopeial Convention, Rockville, MD; 2020. 10.31003/USPNF_M80190_04_01
- Holmlund DE: Physical properties of surgical suture materials: stress-strain relationship, stress-relaxation and irreversible elongation. *Ann Surg.* 1976, 184:189-193. 10.1097/00000658-197608000-00010
- van Rijssel EJ, Brand R, Admiraal C, Smit I, Trimbos JB: Tissue reaction and surgical knots: the effect of suture size, knot configuration, and knot volume. *Obstet Gynecol.* 1989, 74:64-68.
- Wong YR, McGrouther DA: Biomechanics of surgical knot security: a systematic review. *Int J Surg.* 2023, 109:481-490. 10.1097/JS9.0000000000000298
- Zimmer CA, Thacker JG, Powell DM, Bellian KT, Becker DG, Rodeheaver GT, Edlich RF: Influence of knot configuration and tying technique on the mechanical performance of sutures. *J Emerg Med.* 1991, 9:107-113. 10.1016/0736-4679(91)90313-5
- Batra EK, Franz DA, Towler MA, Rodeheaver GT, Thacker JG, Zimmer CA, Edlich RF: Influence of surgeon's tying technique on knot security. *J Appl Biomater.* 1993, 4:241-247. 10.1002/jab.770040305
- Tidwell JE, Kish VL, Samora JB, Prud'homme J: Knot security: how many throws does it really take?. *Orthopedics.* 2012, 35:e532-e537. 10.3928/01477447-20120327-16
- Trimbos JB, Van Rijssel EJ, Klopper PJ: Performance of sliding knots in monofilament and multifilament suture material. *Obstet Gynecol.* 1986, 68:425-430. 10.1097/00006250-198609000-00029
- Davis DA, Pellowski DM, Rawdon EJ: All monofilament knots assume sliding conformation in vivo. *Dermatol*

- Surg. 2013, 39:729-733. 10.1111/dsu.12112
15. Muffly TM, Boyce J, Kieweg SL, Bonham AJ: Tensile strength of a surgeon's or a square knot. *J Surg Educ.* 2010, 67:222-226. 10.1016/j.jsurg.2010.06.007
 16. Brouwers JE, Oosting H, de Haas D, Klopper PJ: Dynamic loading of surgical knots. *Surg Gynecol Obstet.* 1991, 173:443-448.
 17. Lee ACH, Fahmy RRR, Hanna GB: Objective evidence for optimum knot configuration. *World J Surg.* 2008, 32:2736-2741. 10.1007/s00268-008-9764-9
 18. Johannis P, Baek C, Grandgeorge P, Guerid S, Chester SA, Reis PM: The strength of surgical knots involves a critical interplay between friction and elastoplasticity. *Sci Adv.* 2023, 9:eadg8861. 10.1126/sciadv.adg8861
 19. Dinsmore RC: Understanding surgical knot security: a proposal to standardize the literature. *J Am Coll Surg.* 1995, 180:689-699.
 20. Abellán D, Nart J, Pascual A, Cohen RE, Sanz-Moliner JD: Physical and mechanical evaluation of five suture materials on three knot configurations: an in vitro study. *Polymers (Basel).* 2016, 8:147. 10.3390/polym8040147
 21. Erten Taysi A, Taysi NM, Sismanoglu S: Does knot configuration improve tensile characteristics of monofilament suture materials?. *J Oral Maxillofac Surg.* 2023, 81:72-79. 10.1016/j.joms.2022.09.006
 22. Taysi NM, Erten Taysi A, Ercal P, Sismanoglu S: Mechanical performance of nonabsorbable monofilament suture materials tied with different suturing techniques under various knot configurations: an in vitro study. *J Funct Biomater.* 2025, 16:428. 10.3390/jfb16120428
 23. Cobb WS, Burns JM, Kercher KW, Matthews BD, Norton HJ, Heniford BT: Normal intraabdominal pressure in healthy adults. *J Surg Res.* 2005, 129:231-235. 10.1016/j.jss.2005.06.015
 24. Förstemann T, Trzewik J, Holste J, Batke B, Konerding MA, Wolloscheck T, Hartung C: Forces and deformations of the abdominal wall: a mechanical and geometrical approach to the linea alba. *J Biomech.* 2011, 44:600-606. 10.1016/j.jbiomech.2010.11.021
 25. Höer J, Wetter O: Miniaturized sensors registering the long-term course of suture tension in vivo under varying intra-abdominal pressure. *Sensors (Basel).* 2018, 18:1729. 10.3390/s18061729
 26. Marsidi N, Vermeulen SAM, Horeman T, Genders RE: Measuring forces in suture techniques for wound closure. *J Surg Res.* 2020, 255:135-143. 10.1016/j.jss.2020.05.033
 27. Edsfieldt S, Rempel D, Kursk K, Diao E, Lattanza L: In vivo flexor tendon forces generated during different rehabilitation exercises. *J Hand Surg Eur Vol.* 2015, 40:705-710. 10.1177/1753193415591491
 28. Rodeheaver GT, Thacker JG, Edlich RF: Mechanical performance of polyglycolic acid and polyglactin 910 synthetic absorbable sutures. *Surg Gynecol Obstet.* 1981, 153:835-841.
 29. Rodeheaver GT, Thacker JG, Owen J, Strauss M, Masterson T, Edlich RF: Knotting and handling characteristics of coated synthetic absorbable sutures. *J Surg Res.* 1983, 35:525-530. 10.1016/0022-4804(83)90043-4
 30. van Leeuwen N, Trimbois JB: Strength of sliding knots in multifilament resorbable suture materials. *Gynecol Surg.* 2012, 9:433-437. 10.1007/s10397-012-0753-5