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How to tie dangerous surgical knots: easily. Can we avoid this?

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ABSTRACT

Objective Secure knots are essential in all areas of surgical, medical and veterinary practice. Our hypothesis was that technique of formation of each layer of a surgical knot was important to its security.
Design Equal numbers of knots were tied, by each of three groups, using three techniques, for each of four suture materials; a standard flat reef knot (FRK), knots tied under tension (TK) and knots laid without appropriate hand crossing (NHCK). Each knot technique was performed reproducibly, and tested by distraction with increasing force, till each material broke or the knot separated completely.
Setting Temporary knot tying laboratory.
Materials The suture materials were, 2/0 polyglactin 910 (Vicryl), 3/0 polydioxanone, 4/0 poliglecaprone 25 (Monocryl) and 1 nylon (Ethilon).
Participants Three groups comprised, a senior surgeon, a resident surgeon and three medical students.
Outcome measures Proportion of each knot type that slipped, degree of slippage and length of suture held in loop secured by each knot type.
Results 20% of FRK tied with all suture materials slipped; all knots tied with the other two techniques, with all materials, slipped, TK (100%) and NHCK (100%). The quantitative degree of slip was significantly less for FRK (mean 6.3%–, 95% CI 2.2% to 10.4%) than for TK (mean 312%, 95% CI 280.0% to 344.0%) and NHCK (mean 113.0%, –95% CI 94.3% to 131.0%).
The mean length of suture in loops held within (FRK mean 25.1 mm 95% CI 24.2 to 26.0 mm) was significantly greater than mean lengths held by the other techniques (TK mean 17.0 mm, 95% CI 16.3 to 17.7 mm), (NHCK mean 16.3 mm, 95% CI 15.9 to 16.7 mm). The latter two types of knot may have tightened more than anticipated, in comparison to FRK, with potential undue tissue tension.
Conclusion Meticulous technique of knot tying is essential for secure knots, appropriate tissue tension and the security of anastomoses and haemostasis effected.

Key messages

What is already known about this subject?

- The study design was simple, with equal numbers of knots tied for each technique, and for each material.

What are the new findings?

- Only a small number of participants tied knots, limiting any assessment to the effect of the knot tying technique. No inference could be drawn regarding the effect of seniority of participant.

How might these results affect future research or surgical practice?

- A relatively small number of knots were tied with each of the materials limiting more detailed assessment of the effect of the suture material and size on knot security, or whether material and size had any significant influence.

INTRODUCTION

Knot tying is an essential basic practical skill required by all surgeons, veterinary surgeons and any clinician engaged in patient procedures, in all medical as well as surgical specialties. Secure knots that will not slip or fail, are essential for safe surgical and interventional practice, ensuring haemostasis, the integrity of anastomoses, secure and appropriate apposition of wounds, and security of interventional devices. A number of papers have investigated what type of knot could be considered to be best, even looking at the addition of surgical glue to aid security.[1–43] What has not been assessed, in objective detail, is the influence of the actual technique of formation of each layer of the knot on the integrity and security of a square surgical knot, rather than what type of knot.

The security of a knot tied with any material relies on the friction between layers of material applied to make the knot, and the greater the lengths of both sections of suture brought firmly together to entwine and hold against each other, the greater the friction and security of the knot.[1 44 45]

The advent of more modern suture materials, and more monofilament sutures, has led us to apply more layers of material, or more 'throws', to create secure knots as these materials are considered to be more slippery than older materials, and the current recommendation is that we should apply at least six layers of material when securing knots with a monofilament material, such as polypropylene or nylon.[2 3 13 21 46–49] However, the number of 'throws' or layers of suture laid in each knot could be irrelevant if the technique with which the knot is formed is inadequate.[1 14 36–38]

This initial study assessed the impact of technique of knot formation on the integrity and security of standard surgical reef knots, tied using four commonly used suture materials of varying thickness, or strength, and performed by three grades of surgeon, a senior consultant, a surgical trainee who had previously been taught on the Intercollegiate Basic Surgical Skills course,[50] and three medical students. The intention was to determine the influence of technique on the integrity of surgical reef knots, the most commonly used form of knot in surgical procedures; size and strength of the suture material, and experience of the operating surgeon were considered to be less likely to be important.[15 26 28 30 33 40 46–48 51 52 53 54 55]

MATERIALS AND METHODS

Three techniques of tying a surgical reef knot were determined and designed so that each participating surgeon would tie each of the three knots in a reproducible manner common to all participating surgeon groups. Each knot was tied using a needle holder, with instrument tying techniques to facilitate reproducibility between all three surgeon groups.

The first technique was creation of a flat reef knot (FRK) with each layer of the knot, or 'throw', formed with equal and opposite movements of the hands and needle holder, so that each hand crossed each other at an angle of 180 degrees, placing each layer of the knot at precisely the same level, or plane, as the knot itself, ensuring that equal amounts of each end of the suture material used were placed and intertwined in a flat horizontal layer (figure 1).

The second technique was designed to mimic a method where some surgeons maintain tension on a knot to try and prevent it potentially loosening during tying, such as that employed by some when tying a knot at depth (TK). This is usually performed by keeping one end of the suture material stiff to maintain tension on the knot,

Figure 1 Flat reef knot with equal lengths of both ends of suture in knot.

Figure 2 Knot tied under tension producing inadvertent slip knot.

while forming the knot predominantly with the other end. This was performed in this study by keeping one end of the suture tense in a vertical plane, but moving the other end of the suture material producing equal and opposite movements across the knot so that each hand movement was at an angle of 180 degrees to the other, but only with one hand rather than both (figure 2). All layers were placed in the same horizontal plane.

The third technique was designed to mimic a type of mistake where the operating surgeons forgets, or neglects, to remember to cross their hands with each layer of the knot so they neglect to produce equal and opposite hand movements with each layer of the knot (knots laid without appropriate hand crossing, NHCK). Each surgeon would diligently form each layer of the knot as if they intended to perform equal and opposite movements of the hand, alternating formation of layers that should be laid in a downward direction with those that should be laid in the opposite upward direction, but each layer was completed with one hand always moving in a downward direction towards the surgeon (figures 3 and 4). All layers of the knot were placed in one horizontal plane perpendicular to the knot.

A senior consultant surgeon, a junior surgeon and a group of three medical students, each tied ten knots of each of the three techniques, using four suture materials of different calibres, three monofilament, 4/0 poliglecaprone 25 (Monocryl), 3/0 polydioxanone (PDS) and no.1 nylon (Ethilon) and one braided suture, 2/0 polyglactin 910 (Vicryl), provided by Ethicon Greece. All performed these knots at one centre, on one study day. Each knot was tied across an apparatus designed to test its strength and integrity, analogous to that used in other

Figure 3 First layer of knot.

studies on strength of knots.[22 28 56 57] This consisted of a chain attached to a fixed clamp which was then tied to a spring loaded weight measuring device that allowed incremental increases in the weight force applied to the knot and measurement of it (figure 5).

Once the knot was created, each end of the knot was marked with an indelible marker, rapid drying Tippex marker for 2/0 polyglactin 910 (Vicryl), 3/0 PDS and No. 1 nylon (Ethilon) sutures, and blue indelible dye for 4/0 poliglecaprone 25 (Monocryl) sutures. The pressure applied to each knot was increased incrementally till one of three final events occurred; the knot breaks completely with no evidence of slippage of the knot prior to rupture, slippage of the knot and then rupture of the suture, or complete failure of the knot as it slips and completely unravels. Each outcome was recorded, and each suture was photographed following its final outcome. The force at which each knot broke or slipped was measured. The degree by which a knot slipped when tested, was determined by measuring the amount of suture material that appeared, between the indelible markers applied to each end of the suture as it met the knot prior to testing, and the knot itself following application of force (figures 6 and 7). The amount of material that appeared at either end of the knot following application of sufficient force to break it, or cause it unravel, was measured using digital

Figure 4 Second layer of knot when operator failed to cross-hands appropriately.

Figure 5 Suture tied across metal rings ready for distraction and testing.

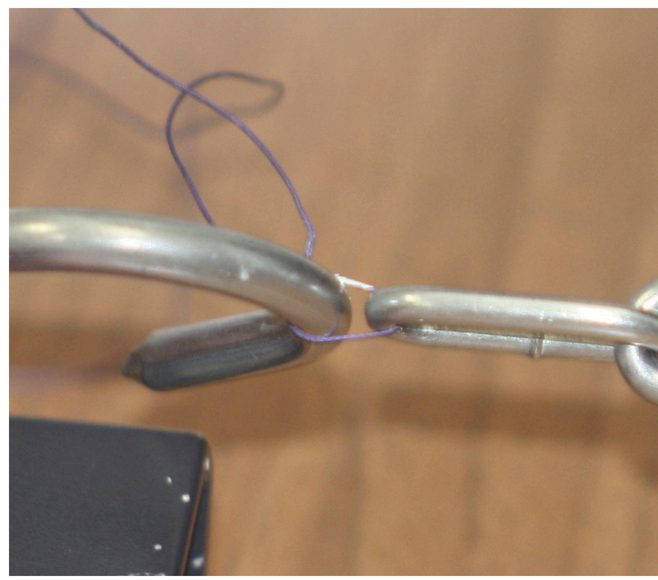

Figure 6 Suture being distracted in test bed, length of suture held in loop within test bed.

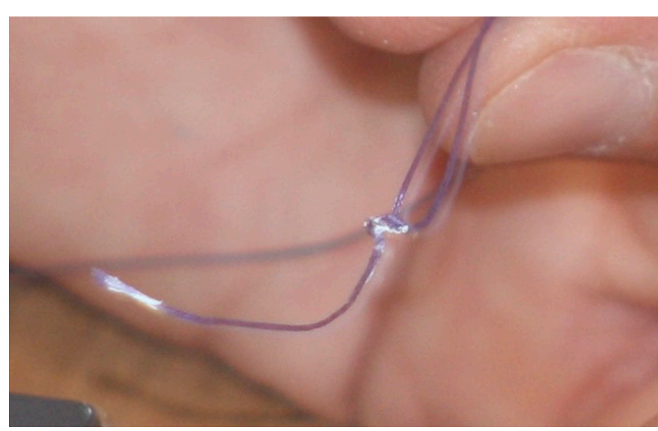

Figure 7 Minimal slippage of knot prior to rupture of loop in suture by distraction in test bed.

Table 1 Number of knots tied with each method, and proportion of knots tied with each method that slipped on testing, mean length of slippage MM, and proportional increase in amount of suture material held within knot post slippage, for each method and 95% CI

Method of formation of square reef knot	No of knots tied	No and proportion (%) of knots that slipped on testing	Mean length of slippage, mm and proportional degree of slippage, (%), recorded for knot method	95% lower CI, mm (%)	95% upper CI, mm (%)	Median length of slippage mm
Flat reef knot	120	24 (20)	1.2 (6.3)	0.5 (2.2)	2.0 (10.4)	0.0
No hand crossing knot	120	120 (100)	**18.5** (**113.0**)	**15.5** (**94.3**)	**21.5** (**131.0**)	**11.9**
Knot tied under tension	120	120 (100)	**50.6** (**312.0**)	**45.9** (**280.0**)	**55.4** (**344.0**)	**51.5**

callipers, compared with the length of suture material included in the loop held by the original knot, and expressed as a percentage proportion of the length of suture included in that loop.

Figures 6 and 7 (Demonstrating length of material incorporated in loop held by the knot, prior to breakage on testing, and minimal slippage as demonstrated by suture material beyond white marker on left side (figure 7) post rupture suture.)

The force required to break each knot, or cause it to slip and unravel, was measured using the spring loaded weight measuring device and expressed in kilograms force.

The results obtained were tested for statistical significance by determining their means and 95% CI.

RESULTS

Equal numbers of each type of knot technique were tied (120) (table 1), equal numbers of knots by each surgeon group (120) (table 1), and equal amounts of each suture material were used with each technique (90) (table 2). Each surgeon group tied 10 knots of each of the three knot types, with each of the four suture materials, producing a total of 360 knots for testing and assessment.

Knot slippage

Twenty per cent of knots tied with all suture materials, by all surgeon groups, using an FRK technique with both hands crossing at 180 degrees to each other, and all layers of the knot laid in the same plane as the knot, subsequently slipped to some degree on testing. 100% of knots tied with one hand maintaining tension on the knot (TK), and 100% of those tied with one hand always moving in a downward direction (NHCK), slipped. In addition, the mean degree of slippage, as measured as a proportional increase in the amount of material that appeared between the indelible markers and the knot itself, or as the mean length of extra material measured in mm, following formation of an FRK (6.3% 95% CI 2.2% to 10.4%) (1.2 mm, 95% CI 0.5 to 2.0 mm), was significantly less than the mean degrees of slippage of knots formed with the other two techniques, with one hand holding the knot under tension (TK) (312.0%, 95% CI 280.3% to 343.7%) (50.6 mm, 95% CI 45.9 to 55.4 mm), and with one hand always moving in a one direction, rather than

Table 2 Number of knots tied with each suture material, proportion of each that slipped on testing, mean degree of slippage in MM and proportional increase in amount of suture material held within each knot after slippage (%), for each suture material and 95% CI

Suture material	No of knots tied with suture material	No and proportion of knots that slipped n (%)	Mean length of slippage of knots tied with each suture material mm, and proportional increase in length of suture material held within knot post slip (%)	Lower 95% CI of mean length and mean proportion of slippage mm (%)	Upper 95% CI of mean length and mean proportion of slippage mm (%)	Median slippage mm
2/0 polyglactin (Vicryl)	90	71 (78.9%)	24.2 (136.0)	18.6 (104.0)	29.8 (167.0)	14.0
4/0 poliglecaprone 25 (Monocryl)	90	60 (66.7%)	15.5 (108.0)	10.9 (73.8)	20.2 (142.0)	4.0
3/0 polydioxanone	90	63 (70.0%)	19.1 (119.0)	13.6 (83.0)	24.5 (154.0)	8.6
1 nylon (Ethilon)	90	70 (77.8%)	34.9 (213.0)	**28.6** (**173.0**)	**41.2** (**252.0**)	**27.7**

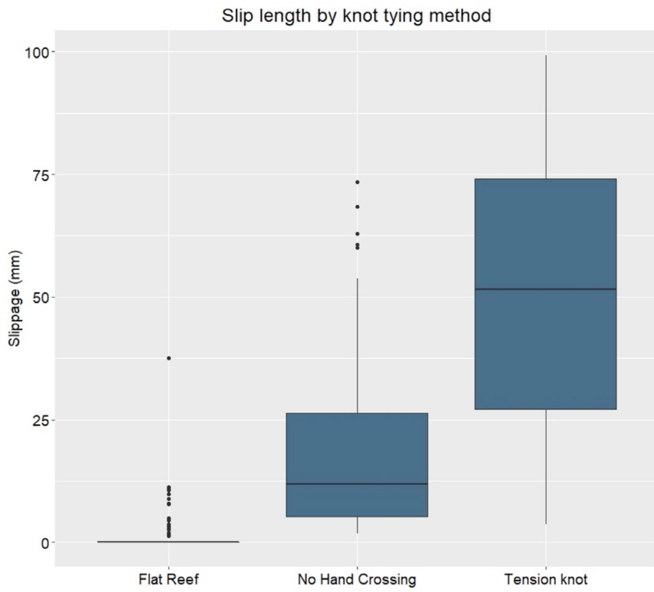

Figure 8 Boxplot displaying the slippage length, and median length and interquartile range ofslippage, in mm by knot tying method.

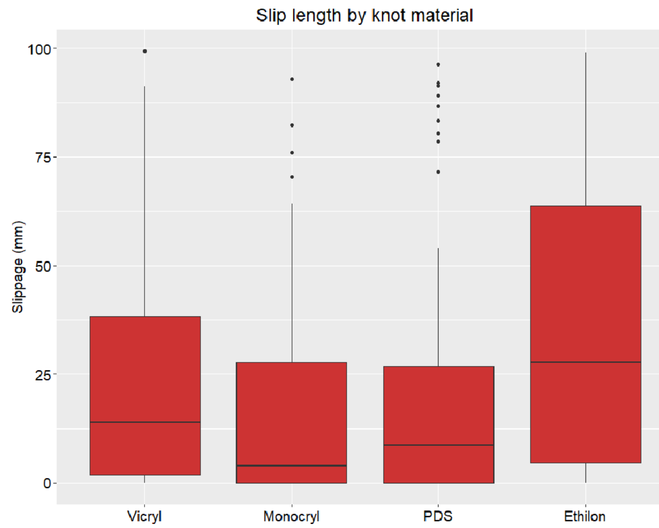

Figure 9 Box plot displaying lengths of slippage, and median slippage and IQR of slippage, for knots tied with eachsuture material. PDS, polydioxanone.

alternately crossing the knot (NHCK) (112.8%, 95% CI 94.3% to 131.4%, 18.5 mm, 95% CI 15.5 to 21.5 mm), (table 2, figure 8)

Of the 90 knots tied with each material, the following numbers and proportions of knots slipped on testing: 2/0 polyglactin (Vicryl) 71 (78.9%), 4/0 poliglecaprone 25 (Monocryl) 60 (66.7%), 3/0 PDS 63 (70.0%) and 1 nylon (Ethilon) 70 (77.8%) (table 2). Similar proportions of the larger suture materials, 2/0 polyglactin (Vicryl) and 1 nylon (Ethilon), slipped on testing. The proportions of knots tied with the smaller diameter suture materials, 4/0 poliglecaprone 25 (Monocryl) and 3/0 PDS appeared to be smaller, but the differences were not significant.

The amounts of slippage of knots tied with the four different materials, as measured by a proportional increase in material held within the knot, did show that those tied with 1 nylon (Ethilon) slipped by a greater length, if they did slip (mean 213.0%, 95% CI 173.0% to 252.0%), than those tied with the smaller diameter suture materials, 4/0 poliglecaprone 25 (Monocryl) (mean 108.0%, 95% CI 73.8% to 142.0%) and 3/0 PDS (mean 119.0%, 95% CI 83.0% to 154.0%). No solid conclusion could be drawn regarding the difference in slippage length with knots tied with 2/0 polyglactin (Vicryl) (table 2, figure 9).

We assessed whether the type of suture material would have an effect on the efficacy of each knot type, determining the mean slippage length within each method for each material type.

No knots tied with 4/0 poliglecaprone 25 (Monocryl) using the FRK technique slipped to any appreciable extent. We observed no significant difference between the lengths of slippage of FRK tied with the other three suture materials. Knots tied with 1 nylon (Ethilon) using the technique of not crossing your hands appropriately, and those tied while keeping the knot under tension, did appear to slip more than knots tied with the same techniques, using the other three suture materials (table 3, figure 10).

We believe this is likely to be due to this large monofilament suture being stronger and less likely to break under tension than smaller diameter suture materials. Knots tied with this material that then slip are less likely to break than those tied with the other materials (table 4).

Knot breakage

Of 360 knots tied, 284 broke on testing, with or without some degree of slippage, 76 slipped completely without breaking.

The proportion of knots that broke completely on testing, whether following some degree of slippage prior to breaking or not slipping at all, was significantly greater for those tied with an FRK technique (0.99, 95% CI 0.98 to 1.00), than those tied with one hand holding the knot under tension (TK) (0.56, 95% CI 0.47 to 0.65), and with one hand always moving in a downward direction (NHCK) (0.82, 95% CI 0.75 to 0.89) One knot of 120 tied with an FRK technique did slip completely, but this compares favourably with 53 knots tied with one hand holding the knot under tension that slipped completely (TK), and 22 of those tied with one hand moving in a downward direction for all layers of the knot (NHCK) (table 5).

On assessing what proportions of knots tied using each of the four suture materials employed in this study, virtually all knots tied with 4/0 poliglecaprone 25 (Monocryl) broke on testing (87, 96.7%). Fewer of those tied with 2/0 polyglactin (Vicryl) (74, 82.2%) and 3/0 PDS (76, 84.4%) broke, and only just over half of those tied with 1 nylon (Ethilon) broke (**47,** 52.2%)**.** (table 4)

Length of suture material included in each knot type prior to testing

The mean lengths of suture material incorporated into knots, that is the length of material in the loop tied

Table 3 Number of knots tied with each suture material, using each technique and length of slippage MM

Method	Material	No of knots tied with technique and suture material	No of knots that slipped	Mean (mm)	Lower CI	Upper CI
Flat Reef Knot (FRK)	2/0 polyglactin (Vicryl)	30	11 (36.7%)	1.4	0.4	2.4
FRK	4/0 poliglecaprone 25 (Monocryl)	30	0 (0%)	**0.0**	**0.0**	**0.0**
FRK	3/0 polydioxanone (PDS)	30	3 (10%)	0.3	–0.1	0.6
FRK	1 nylon (Ethilon)	30	10 (33.3%)	3.3	0.5	6.0
No Hand Crossing Knot (NHCK)	2/0 polyglactin (Vicryl)	30	30 (100%)	19.9	15.1	24.8
NHCK	4/0 poliglecaprone 25 (Monocryl)	30	30 (100%)	7.1	2.5	11.7
NHCK	3/0 PDS	30	30 (100%)	13.6	9.0	18.3
NHCK	1 nylon (Ethilon)	30	30 (100%)	**33.2**	**26.9**	**39.6**
Knot tied under tension (TK)	2/0 polyglactin (Vicryl)	30	30 (100%)	51.4	41.5	61.2
TK	Monocryl4/0 poliglecaprone 25 (Monocryl)	30	30 (100%)	39.6	31.7	47.5
TK	3/0 PDS	30	30 (100%)	43.4	32.1	54.6
TK	1 nylon (Ethilon)	30	30 (100%)	**68.3**	**62.2**	**74.4**

around the hooks held by the knot was measured for all 360 knots. The average lengths of suture material included in the loop for TK tension (mean 17.0mm, 95% CI 16.3 to 17.7mm), and those tied without the operator crossing their hands (NHCK mean 16.3mm 95% CI 15.9 to 16.7mm) were significantly lower than that for (FRK mean 25.1mm, 95% CI 24.2 to 26.0mm). (table 6). This would suggest that that the first two types of knot may tighten more than anticipated, once they are initially formed, in comparison to FRK, and this further tightening may potentially produce undue tissue tension, which may affect tissue viability and healing.

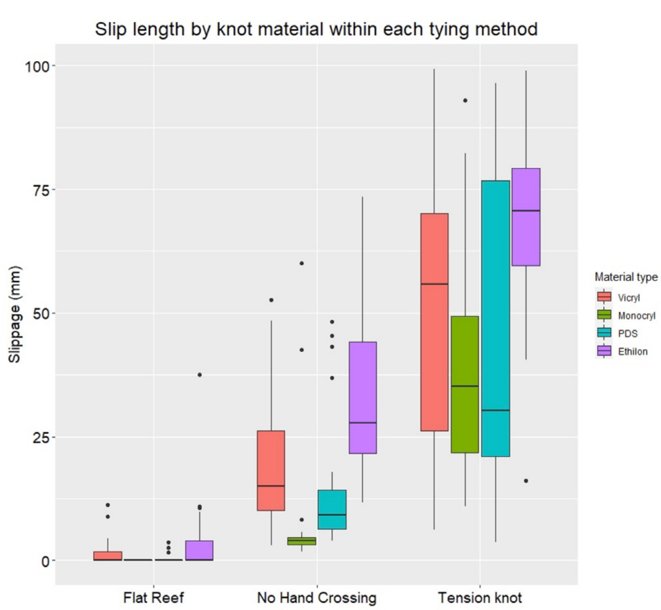

Figure 10 Box plot of slip lengths of knots tied with each of the three techniques, using the four suture materials. PDS, polydioxanone.

DISCUSSION

The ability to tie a reliable and secure knot has always been, and remains, an essential skill for any surgeon, veterinary surgeon, or clinician engaged in any practical clinical discipline,[1] and even with the advent of new technological aids and robotic machines to aid our surgical practice,[58–60] formation of a secure knot remains an essential part of an individual surgeon's or practitioner's craft. In our study, the majority of knots tied with an FRK technique were secure, with no slippage at all, and of those that did slip, the proportional slip was small. Knots tied with this technique, preformed carefully to ensure equal and opposite lengths of suture were entwined, could be considered to be reliable. Those tied with the other two techniques were not secure. All of the latter two types slipped, with all of the materials used, and all tied by each surgeon group.

The degree to which these knots tied with the other two techniques slipped, was remarkable, particularly those tied with one hand maintaining tension on the knot at all times (table 1, figure 8). Those tied with a technique that mimicked a surgeon failing to cross their hands appropriately slipped by more than 100%, those tied by a technique mimicking a surgeon maintaining tension on the knot throughout its formation, as may occur tying in a

Table 4 Number and proportion of knots tied using each suture material that broke on testing

Suture material used for knot formation	No of knots formed	No of knots that broke on testing	Proportion of knots formed that broke on testing %
2/0 polyglactin (Vicryl)	90	74	82.2
4/0 poliglecaprone 25 (Monocryl)	90	87	96.7
3/0 polydioxanone	90	76	84.4
One nylon (Ethilon)	90	**47**	**52.2**

difficult location or at depth,[1 31 42 61] more than 300%. In contrast, the mean degree of slip of knots tied with an FRK technique was markedly less, 6.3%. The small mean result may have been influenced by the large denominator, 120 knots in total, but we did observe that the majority of those FRK that did slip only slipped by a small margin.

Though we observed that knots tied with the largest diameter suture material, 1 nylon (Ethilon), once they did slip, appeared to slip to a greater extent than those tied with the other materials, (tables 2 and 3, figures 9 and 10), the proportion of knots using this material that slipped was not markedly greater (table 2). This apparent difference between suture materials was probably due to the inherent greater strength of the larger suture in comparison to the others; only 52% of knots tied with this larger suture broke on testing. (table 4).

All knots tied with 4/0 poliglecaprone 25 (Monocryl), using the FRK technique, held firm and broke on testing, without slippage (table 3, figure 10.[62] We can make no other conclusions regarding results of individual suture materials, only that the technique used markedly influenced the security and reliability of the knot formed, for all the materials used in this study. (tables 1, 3 and 5, figures 8 and 10).

Knots tied with the techniques of maintaining tension on the knot with one hand, and those tied by an operator failing to cross their hands appropriately, included less material in the loop held by the knot than those tied with an FRK technique (table 6). This may be due to knots tied with these techniques being more prone to slip, and these knots may have slipped more tightly again once the first throw was laid, so less material would be subsequently left within the loop secured by the knot.

If such knots can slip more tightly again, following initial formation of the knot, this may lead to undue tension being applied to a suture, and this, in turn, could lead to undue and unintended tension on the suture. This may have a detrimental effect on tissue healing, such as a bowel or ureteric anastomosis, or wound closure. Insecure knots may cause harm not only from loosening and slipping post formation, but also from squashing and crushing tissue inadvertently during their initial formation.

The salient result was the marked difference in the integrity of knots tied with an FRK technique in comparison to those using the other two techniques, and such was the degree of slippage that we should probably consider knots tied with these two other methods dangerous.

Why did these dramatic knot failures occur in our study? Was this a failure of the design of the study, are our results clinically relevant; are we using the wrong type of knot; are modern suture materials too slippery for secure knot formation; and if we accept there is a potential widespread problem with the security of surgical knots in surgical practice in general, can we overcome the problem, or rely on technology to find other ways of securing haemostasis, anastomoses and closure of wounds, other than TK on a suture,[56 58–60] ?

We would suggest that secure and reliable surgical knots can be consistently made with the simple reef knot with modern materials, provided we employ a meticulous technique, for each and every layer, or throw, of each knot.[40 47]

The simple reef knot has been the most commonly used, and taught, surgical knot. The 'Hercules knot', or square knot, has been recorded to have been used in surgical practice in Greece in the first century AD, and the square knot, or reef knot has probably been used in general for 2000 years,[63–65] The reef knot, tied appropriately, was used to hold heavy,

Table 5 Number of knots tied using each knot technique that slipped and broke and slipped completely, and number and proportion that broke on testing

Method of formation of square reef knot	Total no of knots formed that slipped	No of knots that slipped and then broke	No of knots that slipped completely without any suture breakage	Proportion of knots formed that broke and did not slip completely	95% lower CI of proportion	95% upper CI of proportion
Flat reef knot	24	23	1	0.99	0.98	1.00
No hand-crossing knot	120	98	22	**0.82**	**0.75**	**0.89**
Knot tied under tension	120	67	53	**0.56**	**0.47**	**0.65**

Table 6 Mean lengths of suture material incorporated into loop holding hooks in test bed, for each type of knot method

Method of formation of square reef knot	Total no of knots formed	Mean length of suture material incorporated into loop held by knot mm	95% lower CI of mean	95% upper CI of mean
Flat reef knot	120	25.1	24.2	26.0
No hand-crossing knot	120	**16.3**	**15.9**	**16.7**
Knot tied under tension	120	**17.0**	**16.3**	**17.7**

Results in bold are significantly different.

Figure 11 Flat reef knot prior to being unreefed.

large wet sails in place, even in the worst of stormy weather, as recommended in sailing texts from the 18th century, and described in instruction books for sailors in the 18th and 19th centuries.[66–68] If such a simple knot can control such a heavy burden in these difficult circumstances, and has been used so extensively, and for so long in surgical practice,[1 63] why did we observe such a problem with those tied with two techniques in this study, and failure rates of 24%–80% reported for reef knots tied by experienced surgeons and in studies on teaching knots to students and junior surgeons[1 57 69] ? The answer may lie in how reef knots are untied,[70] and in the nature of modern surgical suture materials.

Sailors can untie, or 'unreef' a knot by pulling on one strand of the knot, this will change the configuration of the

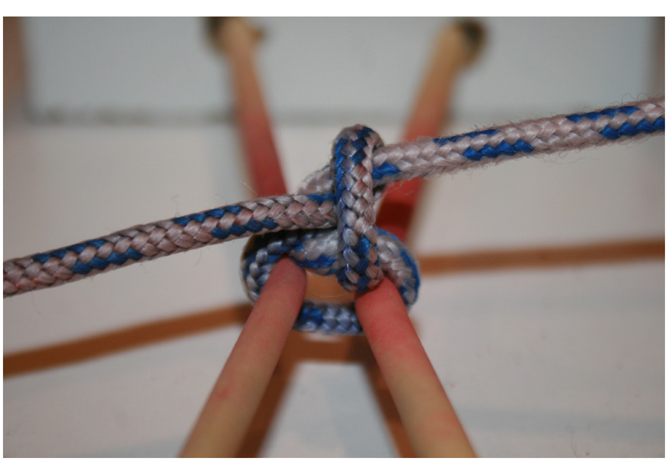

Figure 12 Initial effect of pulling on one end of reef knot causing initial loosening.

Figure 13 Final effect of pulling on one end of reef knot leading to loosening of knot.

knot so that there will be unequal amounts of the two strands of rope in the knot, and one strand can adopt a straight configuration reducing its frictional surface in contact with the other strand, so that it can be undone (figures 11–13).[44 70]

The two knot techniques that produced a failure rate of 100% would have laid unequal amounts of the two suture strands within the knot, reducing the friction between the two strands (figures 2 and 4).

A knot relies on friction between the strands of material placed in mutual apposition within the knot,[1 44 45 71] and this in turn will rely on the natural friction, or lack of slipperiness, of the suture material, and how well the two strands are laid together to produce as much mutual contact between them. The FRK technique would potentially lead to as much contact as possible between the two strands, provided care is taken to ensure equal amounts of material are placed in the knot (figures 1 and 7). What we did observe, during the course of the study, and on observation of videos of the knots we formed, was that even if participants took as much care as possible in forming the FRK, small twists in the material could lead to a less than perfect apposition of the suture strands at the final laying down of the knot, leading to unequal strand lengths in the final knot. This may make these particular knots less resistant to slipping on testing, and could explain why a proportion of knots tied with our FRK technique slipped, and why some knots tied by senior surgeons in other studies failed.[40 42 51]

Knots rely on friction between the strands of material laid in the knot, and the material must have a level of surface friction sufficient to allow knots to hold.[1 45] Though more modern suture materials would appear to more slippery, and pass through tissue less traumatically than older and traditional materials, even monofilament nylon has sufficient surface friction to allow a simple reef knot to hold.[45]

The study design was simple, relying on a winch applied to a weighing spring, to produce an incremental force to distract two metal hooks tied together with the four, dry, suture materials we tested. Other studies assessing different types of knots, rather than technique of knot formation, have validated the use of such simple techniques and equipment.[2–8 10 22 28 35 57 72] We would suggest that our conclusions on knot security are clinically valid; poor technique can lead to dramatically poor results.

What should we do in clinical practice? This study, and other studies that have compared different types of knots rather than the influence of technique on knot integrity,[1–43] have demonstrated that a proportion of knots can slip. This is a small study, and should probably be viewed as a preliminary study, but the results are clear. Do we abandon using sutures and look at other methods relying on technology, such as stapling devices for all anastomoses, haemostatic devices for haemostasis and vessel control, and staple all wounds,[56 58–60] or do we accept that technique and craft are essential for a successful outcome when forming knots,[40 51] ? Relying on technology would be expensive, and limit our adaptability; we cannot produce sufficient tailor made technological solutions for all surgical eventualities we may encounter, and technology is intended to aid our craft and abilities, not replace it. Instead, we could improve our individual ability to lay secure, flat knots, in all circumstances and anatomical situations, and employ it universally. If a simple task as tying a secure knot can be so affected by technique, should we consider assessing the technique of all our manoeuvres and procedures?

ARTICLE SUMMARY

- The majority of knots tied with an FRK technique appeared to be secure.
- All knots tied with the other two techniques, with all materials, slipped on testing and slipped markedly.
- The length of suture material within loops held by FRK was greater than in those held by knots tied with the other two techniques, suggesting these latter two slipped tighter during knot formation
- Given the marked difference in the security of knots tied by the techniques studied, even though a relatively small number of knots were tied and assessed in this study, all clinicians and health professionals engaged in any invasive procedures should assess their knot tying techniques to ensure their knots are secure.

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Contributors ED: main author, participant in experiments, statistical analysis, design of study, editing figures, data storage and processing. SS: edited paper, participant in experiments, design of study with main author, photography and design of figures. ES: facilitator of location for study, participant in experiments, data storage and handling, statistical analysis, participant in design of study and academic guidance on handling on analysis of data. EPo: edited paper, participant in experiments, sourcing materials and equipment for experiments, image capture for figures. IP: edited paper, participant in experiments, image capture for figures. EPa: provision of equipment for experiments and measurements, edited paper, participant in experiments, image capture for figures. LS: data handling and management, detailed statistical analysis and advice on suitable models of data assessment, completion of plot diagrams, editing paper. DZ: provision of location, equipment and resources for study, participation in design of study and data analysis, academic advice and guidance.

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