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Analysis and Physics of Laparoscopic Intracorporeal Square-Knot Tying

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ABSTRACT

Square knots are often used in open surgery to approximate tissue borders or tie off tubular structures like vessels or ducts. Three common methods are used for surgical square-knot tying: one-hand tying, two-hand tying, and the instrument-tying technique. Two types of suture placements are studied in both the open and laparoscopic surgical fields. The first called *equal length* has suture segment ends placed at equal distances from the tying site. The second called *unequal length* has one suture end further away from the tying site than the other. Laparoscopic intracorporeal square-knot tying maneuvers are analyzed herein. Mechanical analysis of square-knot tying movements reveals that regardless of location or method used in construction, all square knots consist of 2 half-knots. For study purposes, these sets of movements are identified in laparoscopy as *maneuver A* and *maneuver B*. Further breakout of these maneuvers reveals that they consist of 5 motions. This study reveals that 16 different ways exist to place a square knot by means of the laparoscopic intracorporeal technique. It is likely that difficulty mastering this essential skill is not just the result of poor instrumentation, improper port placement, or the limitations of a 2-dimensional video image. It may also be attributed to mixing up the different square-knot tying techniques during random practice exercises. This is possible if the surgeon is ignorant of the technical variations present in what most people consider a simple task.

Key Words: Laparoscopic square-knot tying, Laparoscopic physics, Laparoscopic education, Laparoscopic trainer, Pelvic trainer.

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Disclosure: The author is the inventor of the MedinaTrainer and president of Borinquen Creative Systems, (McAllen, Texas), which distributes the MedinaTrainer.

INTRODUCTION

Square knots are often used to approximate tissue borders or tie off tubular structures like vessels or ducts. These anatomical features will henceforth be called *tying sites* and described as "TS." Three classic methods exist by which to place surgical square knots in open surgery. The first is called *one-hand tying* (OHT), the second *two-hand tying* (THT), and the third *instrument-tying technique* (ITT).[1]

In OHT, suture ends are most commonly held at unequal lengths (UL), with the nondominant hand holding the longer suture end. The shorter end is placed in the dominant hand, which performs the mechanical motions of wrapping the shorter end around the longer one to create a square knot. This common technique is best described as *one-hand tying–unequal length* (OHT-UL).

One can also perform OHT using equal length (EL) suture ends. In this case, the result is that the dominant hand works at a slower pace, thereby making it a less desirable method. This technique can be called *one-hand tying–equal length* (OHT-EL).

The recommended approach in THT involves placing a suture in such a manner that both ends are at EL from the TS. The necessary hand motions are then carried out to place the first square knot. Additional knots follow the same technique. This traditional method will be referred to as *two-hand tying–equal length* (THT-EL).

It is also possible to create a square knot with THT while using UL suture ends. This less efficient method will be called *two-hand tying-unequal lengths* (THT-UL). Occasionally, one resorts to this technique when a suture end needs to be cut before a tying maneuver can be completed. This can occur when an end becomes knotted or frayed.

The most common way to perform ITT requires that a curved needle be passed, by means of a needle holder, through 2 opposing tissue edges. The suture ends are then drawn up in a UL fashion. The nondominant hand holds the longer suture end, with the needle hanging from it. To construct a square knot, the dominant hand uses the needle holder to maneuver the short suture end around the longer. This method is called, *instrument-tying technique–unequal length* (ITT-UL). An alternative method would be to use EL suture ends. This less efficient method is called *instrument-tying technique–equal length* (ITT-EL). Considerable suture wastage occurs in this last technique, and it is not frequently used, its use being more the sign of a novice than an expert.

Surgical square knots are also known as "reef" knots in the knot-tying literature.[2] References 1 and 2 provide instructions for the hobbyist and surgeon on how to construct traditional square knots. Based on the above analysis, 6 methods are available for constructing a square knot in open surgery. Three of these (OHT-UL, THT-EL, and ITT-UL) are frequently taught and recommended. The other 3 (OHT-EL, THT-UN, and IT-EL) are infrequently relied on.

It is important to note that the previous discussion did not take into consideration the handedness of the surgeon. Mechanical motions performed by right-handed surgeons (RHS) are different from those of left-handed surgeons (LHS). In studying the physics of square-knot tying in open surgery, one must take this important fact into account and consider it a third variable. Adding handedness into the analysis brings our grand total to 12 possible open surgery square knots.

Mathematically, one can arrive at the same result by multiplying together the 3 major variable factors involved in open surgery square-knot tying as follows:

3 Manipulation: OHT, THT, ITT
x 2 Suture length: EL, UL
x 2 Handedness: RHS, LHS
12

To the author's knowledge, the above analysis has not been previously presented. **Table 1** lists the 12 square knots in open surgery. It now appears that what were considered routine maneuvers in the past were not so simple after all. In spite of these complexities, surgeons master square-knot tying. Each one of us settles into his or her favorite tying style–and rarely changes after that. What raised the stakes was the advent of video surgery. Suddenly, "instinctual skills" became very difficult to perform in the new medium.

Table 1.
Major Tying Techniques in Open Surgery

Knot	Abbreviations*
1	OHT-UL-RHS
2	THT-EL-RHS
3	ITT-UL-RHS
4	OHT-EL-RHS
5	THT-UL-RHS
6	ITT-EL-RHS
7	OHT-UL-LHS
8	THT-EL-LHS
9	ITT-UL-LHS
10	OHT-EL-LHS
11	THT-UL-LHS
12	ITT-EL-LHS

OHT=one-hand tying; THT=two-hand tying; ITT=instrument-tying technique; EL=equal-length; UL=unequal length; RHS=right-handed surgeon; LHS=left-handed surgeon.

METHODS

The Medina-Trainer was used to analyze knot-tying movements. This is an open-view laparoscopic simulator that allows use of a camcorder or digital camera connected to a regular television monitor.[3] White cotton crotchet thread is substituted for suture material with half of the lengths dyed black with India ink. This facilitated analysis of all laparoscopic intracorporeal square-knot tying (LIST) suture end-movements.

Different laparoscopic needle holders and grasping instruments were experimented with and no particular preference taken. Digital and video photography were used to analyze mechanical movements. Adobe Photoshop Elements[4] was used in editing the photographs. With this software, the suture lengths are highlighted in the foreground, resulting in better publication photographs.

The camera position was used exclusively in this study, because this is the location most closely resembling movements in the open field. In this position, the surgeon stands behind the camera with the video monitor directly in front.[5] Long, tubular balloons were used to simulate a tubular structure (TS). These were placed on a tissue suspender at a tissue angle of 0 degrees.[6]

Before placing a laparoscopic intracorporeal square knot, one must take into account several considerations. The choice of suture material and gauge size will depend on the structure to be tied. The total suture length should be between 6 inches to 8 inches. Smaller or larger segments of suture result in time-consuming and cumbersome actions. Before starting, one must decide how the suture ends will be placed. The choice is the same as that in open surgery, either by means of EL or UL. Suture length is, therefore, the first variable factor encountered in LIST.

While studying mechanical movements, it soon became apparent that it is necessary to know where in space the first suture end is grasped. This will then determine subsequent events. For simplicity sake, tying maneuvers were studied with the TS placed in both a vertical and horizontal direction. Two areas were created with each placement. With the TS placed in a vertical position, we have a vertical right (VR) and vertical left (VL) space. Placing the TS in a horizontal position results in a horizontal top (HT) and a horizontal bottom (HB) space. Position, is, therefore, the second variable factor in LIST.

Figures 1 and **2** demonstrate the use of a cylinder to represent the TS. A thick, straight line, half white and half black, is used to symbolize the suture being tied. The first white suture half is called *end 1* (E1) and the black half *end 2* (E2). The inset drawings in these figures are a further simplification. Here, a thin line with a black and white circle at each end has replaced the thick black and white line. The white circle represents E1 and the black circle E2.

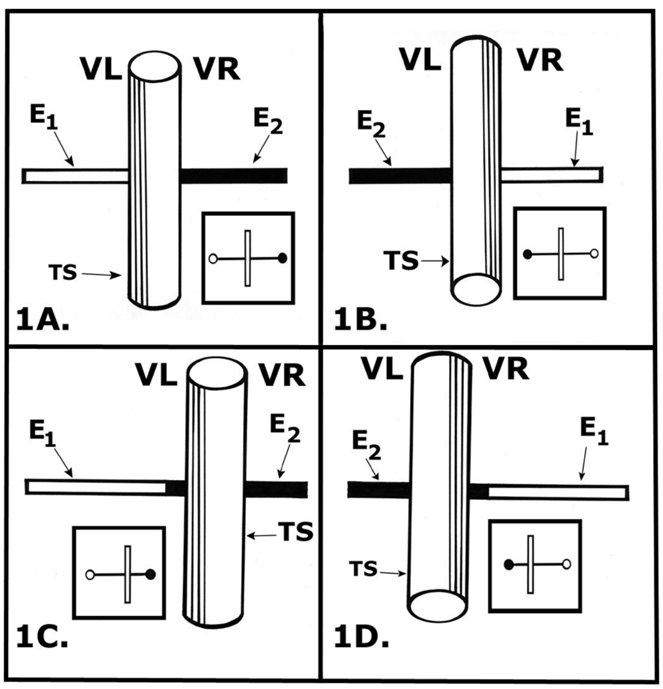


Figure 1. Tubular structure (TS) in vertical position. E_1 = first end grasped; E_2 = second end grasped; VR = vertical right position; VL=vertical left position.

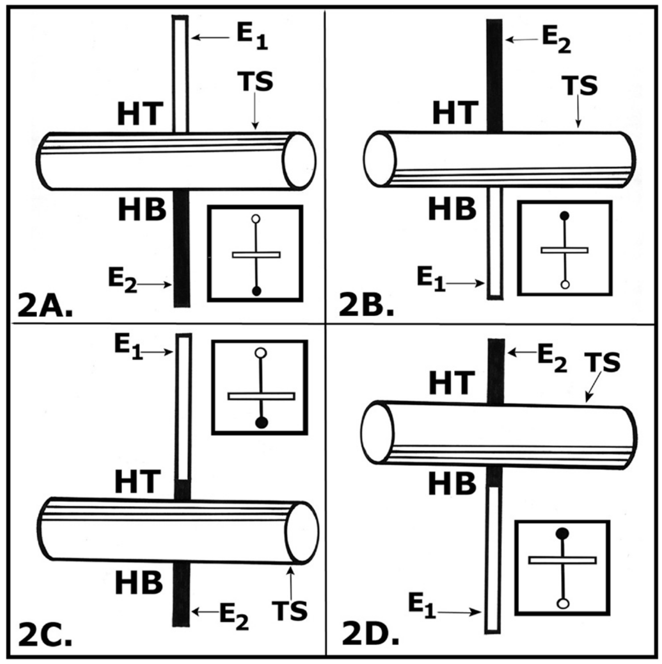


Figure 2. Tubular structure (TS) in horizontal position. E_1=first end grasped; E_2=second end grasped; HT = horizontal top position; HB = horizontal bottom position.

In **Figures 1A** and **1B**, both E1 and E2 are placed at EL under the TS. In **Figure 1A**, E1 is grasped in the VL position. In **Figure 1B**, E1 is grasped in the VR position. **Figures 1C** and **1D** still have the TS in a vertical orientation, but the suture is now placed in a UL fashion. In **Figure 1C**, E1 is grasped in the VL position and in **Figure 1D**, E1 is grasped in VR. **Figure 2** follows the same logic described in **Figure 1**, with the exception of having the TS placed in a horizontal location and the orientation positions now being HT and HB.

A third observation is the necessity to rotate the laparoscopic instrument twice, either clockwise (R+) or counterclockwise (R-), when tying. **Figure 3** illustrates the symbols and abbreviations used to distinguish between the 2 rotations. In **Figure 3A**, the right-facing, curved arrow with the white circle at the end represents the clockwise rotation of a long, first end E1. In **Figure 3B**, the curved arrow with the black circle at the end represents a clockwise rotation of a long, second end E2. **Figure 3C**, resembles **Figure 3B**, except that a short, end E2 is being rotated clockwise. **Figures 3D**, **3E**, and **3F** follow a similar line of reasoning as that of the first 3 figures, with the exception that the left-facing curved arrows represent rotations going in a counterclockwise direction.

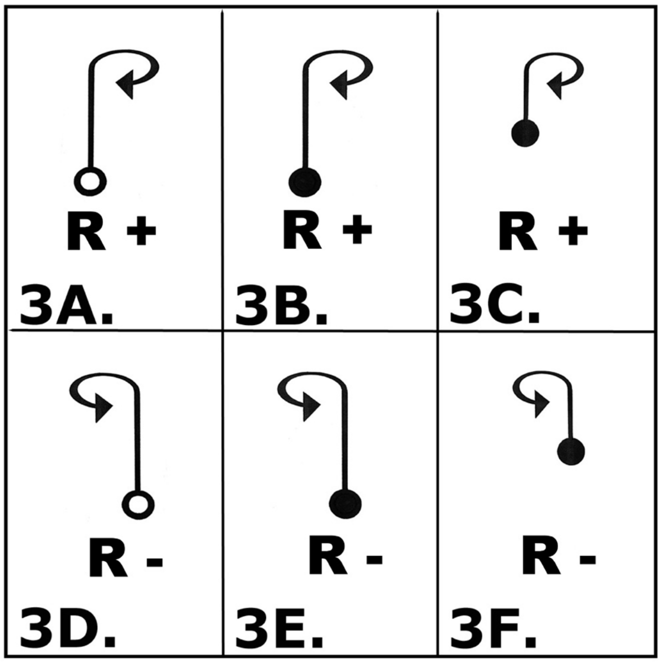


Figure 3. Rotation symbols. R+ = curved arrows going right are clockwise rotations. R- = curved arrows going left are counterclockwise rotations. White circle represents first end, and the black circle represents the second end. Note: Dimension of straight arrow segment (long vs. short) coincides with suture length to be rotated.

For learning purposes, it is helpful to identify the presence of symmetry or asymmetry between the 2 rotations found in square knots. *Equal rotations* (ER) are either 2 clockwise or 2 counterclockwise rotations: R+R+ or R-R-. *Unequal rotations* (UR) are either a clockwise rotation followed by a counterclockwise one, or the other way around, R+R- or R-R+. In summary, rotation is the third variable factor found in LIST.

The new symbols and abbreviations described above are used to represent the mechanical motions necessary for LIST. Symbols to represent complicated movements are commonly used in other areas of skilled activities. Musical notations, used by musicians to play difficult compositions, are one example. Football strategy drawings are another. Here, diagrammatic representations tell players what positions to assume on the field. Of course, to understand any symbol, one must have an interest in the particular activity being represented and willing to try it.

An important similarity between open surgery square-knot formation and LIST is that each square knot is made of 2 half-knots. For study purposes, these sets of movements will be identified in LIST as *maneuver A* and *maneuver B*. Further analysis reveals that each maneuver can be further broken up into 5 motions. These are described in Table 2.

The first 3 motions are different for individual LIST knots. The last 2 motions are constant in all square knots. Since 2 maneuvers are necessary to construct a laparoscopic square knot, it stands to reason that 10 motions are necessary for each square knot. The 10 motions comprise 4 grasping motions, 2 rotations, 2 crossovers, and 2 tightening motions.

RESULTS

One can determine mathematically the total number of square knots that can be performed by means of LIST by multiplying the 3 previously mentioned variables:

  2 Suture length: EL, UL
x 4 Position: VR, VL, HT, HB
x 2 Rotation: R+, R-
———————
  16

The final number is 16. This number is higher than the 12 possibilities previously determined for open surgery. The presence of so many choices could explain the hurdles encountered by many surgeons trying to perform LIST. If you are not aware of the 16 different knots you have to select from in placing a laparoscopic square knot, it will be difficult to back track movements and faithfully reproduce one's actions. Inevitably, you will end up going back and forth confused between different techniques.

In an attempt to analyze the complicated actions involved in LIST, a summary of all the motions required to tie knot K1 are listed in Table 3. It is important to note that K1 starts with the TS in a vertical position, and the suture ends placed in an EL manner. Abbreviations are accompanied

Table 2.
The 5 Motions of a Maneuver

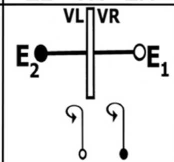
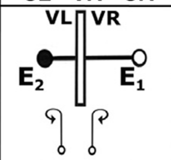
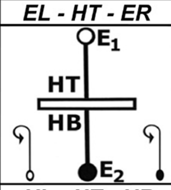
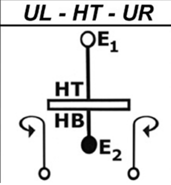
Motion	Description	Abbreviation
Motion 1	First grasp suture end 1	G_1E_1
Motion 2	Rotate grasping instrument, either clockwise or counterclockwise	R+ or R−
Motion 3	Second grasp of either end 1 or 2	G_2E_1 or G_2E_2
Motion 4	Crossover	X
Motion 5	Tighten	T

*G_1=first grasp; G_2=second grasp; R+=rotation clockwise; R−=rotation counterclockwise; X=crossover; T=tighten; E_1=end 1; E_2=end 2.

Table 3.
Mechanical Analysis of Knot K1 With Equal Length-Equal Rotations

Motion	Abbreviation	Description
MA_1	VR: G_1E_1	Maneuver A—Motion 1
		First grab end 1 in the vertical right position
MA_2	R−	Maneuver A—Motion 2
		Rotate instrument counterclockwise
MA_3	VL: G_2E_2	Maneuver A—Motion 3
		Second grab end 2 in the vertical left position
MA_4	X	Maneuver A—Motion 4
		Crossover
MA_5	T	Maneuver A—Motion 5
		Tighten
MB_1	VR: G_1E_2	Maneuver B—Motion 1
		First grab end 2 in the vertical right position
MB_2	R−	Maneuver B—Motion 2
		Rotate instrument counterclockwise
MB_3	VL: G_2E_1	Maneuver B—Motion 3
		Second grab end 1 in the vertical left position
MB_4	X	Maneuver B—Motion 4
		Crossover
MB_5	T	Maneuver B—Motion 5
		Tighten

Table 4.
Maneuvers and Motions of Knots K1, K2, K9, and K10*

Knot	EL - VR - ER	Maneuver A		Maneuver B	
K_1		MA_1	VR: $G_1 – E_1$	MB_1	VR: $G_1 – E_2$
		MA_2	R-	MB_2	R-
		MA_3	VL: $G_2 – E_2$	MB_3	VL: $G_2 – E_1$
		MA_4	X	MB_4	X
		MA_5	T	MB_5	T
Knot	UL - VR - UR	Maneuver A		Maneuver B	
K_2		MA_1	VR: $G_1 – E_1$	MB_1	VL: $G_1 – E_1$
		MA_2	R-	MB_2	R+
		MA_3	VL: $G_2 – E_2$	MB_3	VR: $G_2 – E_2$
		MA_4	X	MB_4	X
		MA_5	T	MB_5	T
Knot	EL - HT - ER	Maneuver A		Maneuver B	
K_9		MA_1	HT: $G_1 – E_1$	MB_1	HT: $G_1 – E_2$
		MA_2	R-	MB_2	R-
		MA_3	HB: $G_2 – E_2$	MB_3	HB: $G_2 – E_1$
		MA_4	X	MB_4	X
		MA_5	T	MB_5	T
Knot	UL - HT - UR	Maneuver A		Maneuver B	
K_{10}		MA_1	HT: $G_1 – E_1$	MB_1	HB: $G_1 – E_1$
		MA_2	R-	MB_2	R+
		MA_3	HB: $G_2 – E_2$	MB_3	HT: $G_2 – E_2$
		MA_4	X	MB_4	X
		MA_5	T	MB_5	T

*MA=maneuver A; MB=maneuver B; VL=vertical left; VR=vertical right; HT=horizontal top; HB=horizontal bottom; G_1=first grasp; G_2=second grasp; E_1=end 1; E_2=end 2; R+=rotation clockwise; R−=rotation counterclockwise; X=crossover; T-tighten. Note: Subscript number following MA or MB denotes the motion.

by a brief description of their meaning. For example, in Maneuver A–Motion 1, (MA_1), end E1 is grasped in the VR position and then rotated counterclockwise (R-) in Maneuver A–Motion 2, (MA_2). In Maneuver B–Motion 1, (MB_1), end E2 is grasped in the VR position and again rotated counterclockwise (R-).

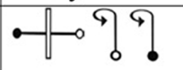
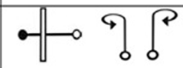
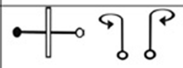
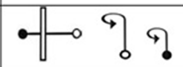
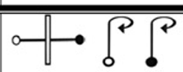
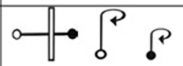
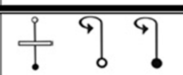
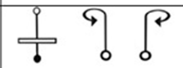
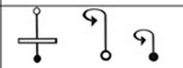
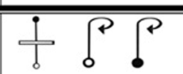
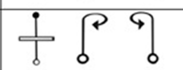
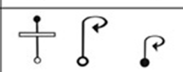
Table 4 concentrates on what the author considers the 4 most useful knots for a right-handed surgeon (RHS): K1, K2, K9, and K10. Knot K2 has the TS in a vertical position, with suture ends placed in a UL manner. K9 is tied with TS in a horizontal position, using EL suture ends. K10 also uses a horizontal TS, but UL ends for tying.

Table 5 lists all 16 knots. The Symbol heading shows a miniature of the inset drawings introduced in **Figures 1** and **2** and 2 curved arrow figures to represent the essential rotations of each maneuver. The last heading "RHS" grades the overall benefits of particular knots for right-handed surgeons. It is based on the author's preferences established after performing hundreds of LIST exercises. The grading system goes from 1 (the best) to 4 (the worst). The best knots to tie are those that result in smooth, effortless movements.

A relationship between types of rotations and the handedness of the surgeon was also observed. The author, an RHS, found it particularly helpful to have a counterclockwise rotation present in the first maneuver. The 4 preferred knots, K1, K2, K9, and K10, all have this feature in common and are number 1 rated knots. Performing a counterclockwise rotation appears to be an easier task for an RHS. While it has not been verified, it is suspected that LHS possibly work better with clockwise rotations.

Knots K1, K2, K9, and K10 can be categorized further, K1 and K9 as *equal lengths– equal rotation* (EL-ER) knots, K2

Table 5.
Major Tying Techniques in Laparoscopic Intracorporeal Square-knot Tying*

Position	Knot	Description	Symbol	RHS
VR	K 1	VR EL ER R- R-		1
	K 2	VR UL UR R- R+		1
	K 3	VR EL UR R- R+		2
	K 4	VR UL ER R- R-		4
VL	K 5	VL EL ER R+ R+		3
	K 6	VL UL UR R+ R-		2
	K 7	VL EL UR R+ R-		2
	K 8	VL UL ER R+ R+		4
HT	K 9	HT EL ER R- R-		1
	K10	HT UL UR R- R+		1
	K11	HT EL UR R- R+		2
	K12	HT UL ER R- R-		4
HB	K13	HB EL ER R+ R+		3
	K14	HB UL UR R+ R-		2
	K15	HB EL UR R+ R-		2
	K16	HB UL ER R+ R+		4

*VR=vertical right; VL=vertical left; HT=horizontal top; HB=horizontal bottom; EL=equal length; UL=unequal length; ER=equal rotations; UR=unequal rotation; R+=clockwise rotation; R−=counterclockwise rotation; RHS=right-handed surgeon.

and K10 as *unequal length–unequal rotation* (UL-UR) knots. Keeping these associations in mind is helpful in remembering particular knot-tying sequences. If you compare the motions of these knot pairs in Table 4 and Table 5, without regard to the position abbreviations (VR, VL, HT, HB), it becomes evident that each pair has identical motions. The only difference between them is the vertically or horizontally placed TS. This important observation has practical applications in learning the maneuvers of the 4 knots. Once the tying motions for K1 and K2 are mastered, it becomes much easier to learn K9 and K10 because of their motion's similarities.

Table 5 provides enough information to construct all 16 knots. For example, one can determine from both the abbreviations and the drawings under the Description and Symbols headings that, knot K3 is performed using EL suture ends, which are placed under a vertically oriented TS. In MA, suture end E1 is grasped in the VR position, and then rotated counterclockwise (R-). In MB, end E1 is rotated clockwise (R+).

The number 2 rated knots in **Table 5** were relatively easy to perform, but not preferred. The number 3 rated knots are difficult for RHS. It is suspected that LHS might experience greater success performing knots K5 and K13. This will have to be verified in future studies. The number 4 rated knots (K4, K8, K12, and K16) are of intellectual interest only. The problem with these knots relates to the fact that a short suture end must be rotated. Laparoscopic rotations are challenging enough with adequate suture length. To perform this motion with insufficient length is a nightmare.

To further illustrate the steps involved in tying K1, K2, K9, and K10, **Figure 4** and **Figure 5** have been provided. These are digital camera images of actual tying exercises. When necessary, a particular motion may have several spot photos to represent it. A lower case letter is placed in alphabetical order at the lower right-hand side of each individual photo to identify these motion sequences.

Figures 4-K1.1 and **4-K1.2** demonstrate the first motion of maneuver A (MA_1, VR: G_1-E_1) for tying K1. It is represented as 2 sequential photos "a" and "b." Here, we follow the passing of the white suture end under the vertical TS to place it in VR. It is in "b" that the actual tying sequence begins. **Figures 4-K1.3** and **4-K1.4** show the second motion of maneuver A (MA_2 R-) for tying K1. Spot photos "a" and "b" are used to demonstrate a counterclockwise rotation.

Other examples are **Figures 6-K9.1**, **6-K9.2**, and **6-K9.3**. Here, the first motion of maneuver A (MA_1, HT: G_1 E_1) has 3 spot photos, "a," "b," and "c." The actual tying sequence does not begin until the "c" photo is reached. Here the white end is grasped in the HT position in an EL fashion. It is hoped that these examples will allow the reader to interpret the remaining illustrations.

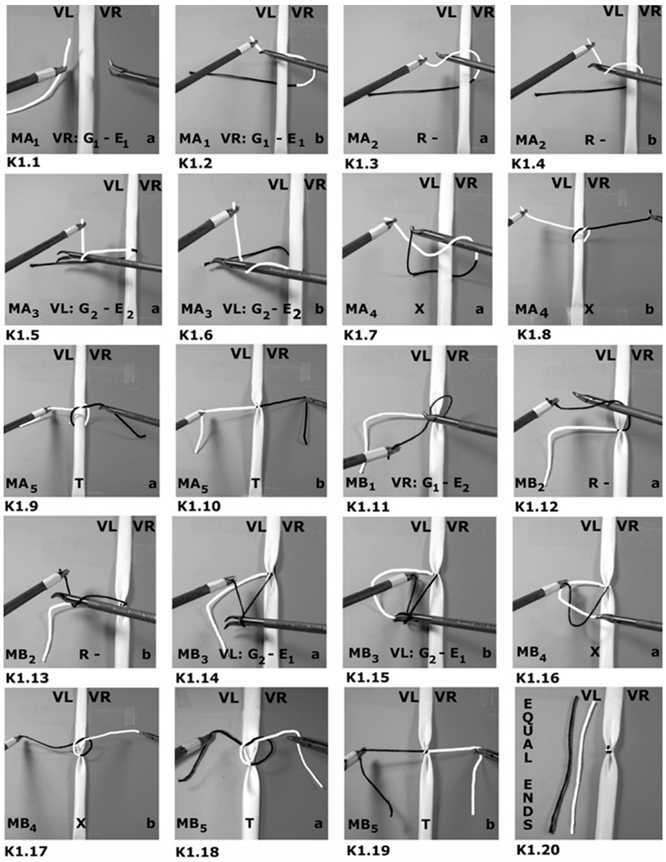


Figure 4. Laparoscopic intracorporeal square knot 1 (equal lengths–equal rotations).

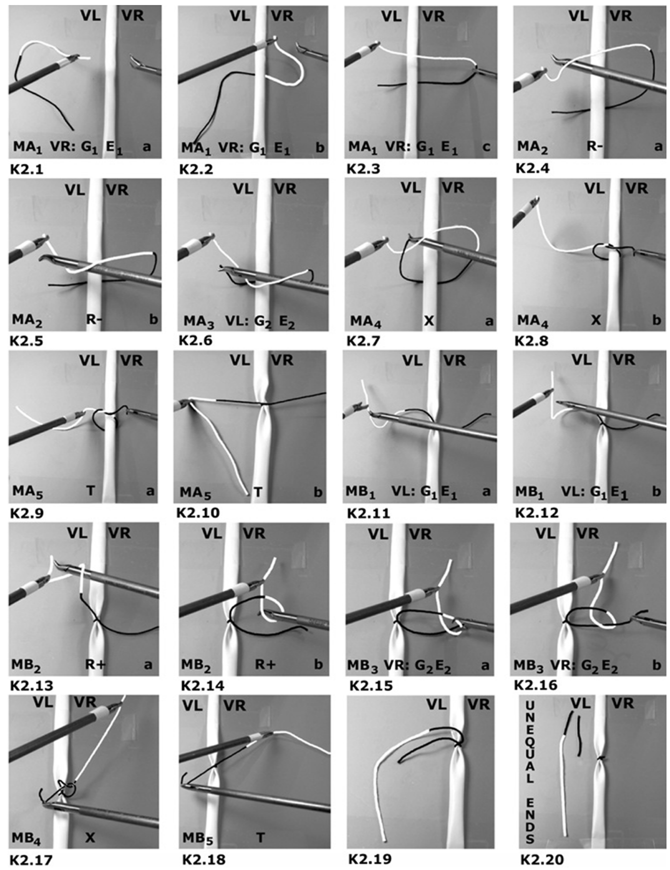


Figure 5. Laparoscopic intracorporeal square knot 2 (unequal lengths–unequal rotations).

DISCUSSION

Formation of a square knot, in both open and laparoscopic surgery, involves 2 common features. First is the presence of 2 half-knots for each square knot. Second is the need to determine suture end length. Other variable factors are unique to the particular surgical style being performed, either open or laparoscopic.

Manipulation is a variable factor present only in open surgery. Here, the surgeon can choose between tying with 2 hands, 1 hand, or an instrument. The first 2 options are not available in standard laparoscopy, because all intracorporeal square-knot tying is performed with instruments. Hand-assisted laparoscopy was not taken into consideration in this study. Perhaps in future studies, this hybrid surgical approach can be added as an additional variable factor.

Starting positions, such as VR, VL, HT, and HB, while important in video surgery, are of little consequence in open surgery. Here, an infinite number of hand positions are available to chose from and to be able to move instruments around in. Laparoscopic surgery has forced a trade off between a magnified view at the operative site and decreased instrument movement.

Murphy[6] in his analysis of square-knot tying techniques, during both instrument and hand-finger movements, confirmed the need for 2 "half-hitches." He uses this term in both open and laparoscopic surgery. The current study distinguishes the same expression by using the term "half-knot" for open surgery and "maneuvers A & B" for intracorporeal knot tying.

Murphy identified "12 ways to create a square knot" in both open and laparoscopic surgery. By taking a different analytical approach, the current study reveals that 12 open surgery square-knot possibilities and 16 intracorporeal laparoscopic possibilities actually exist. Murphy stated, "During open surgery, the half-hitch can be tied by two different actions: an instrument tie method, a one-hand, or a two-hand-tie method."

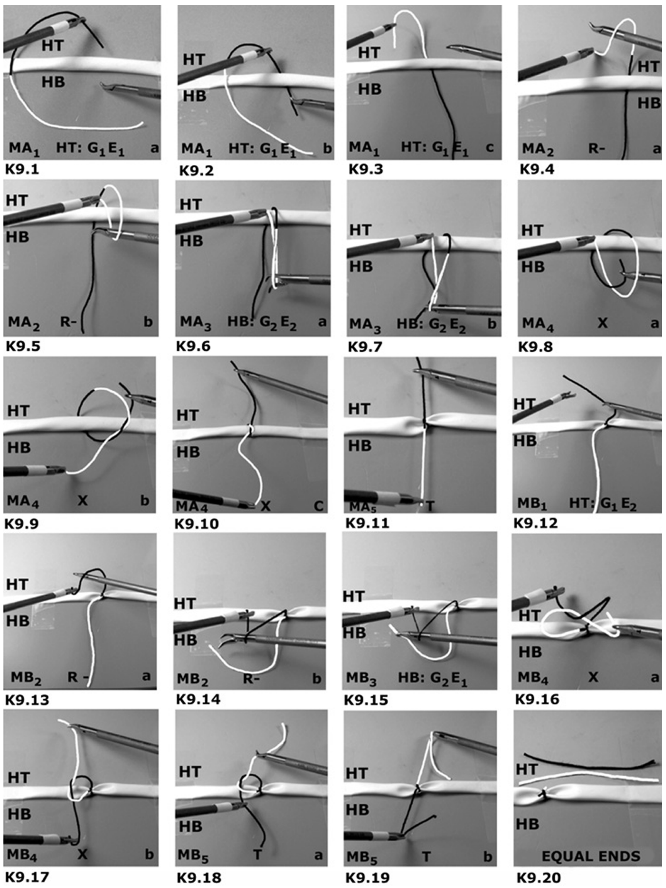


Figure 6. Laparoscopic intracorporeal square knot 9 (equal lengths–equal rotations).

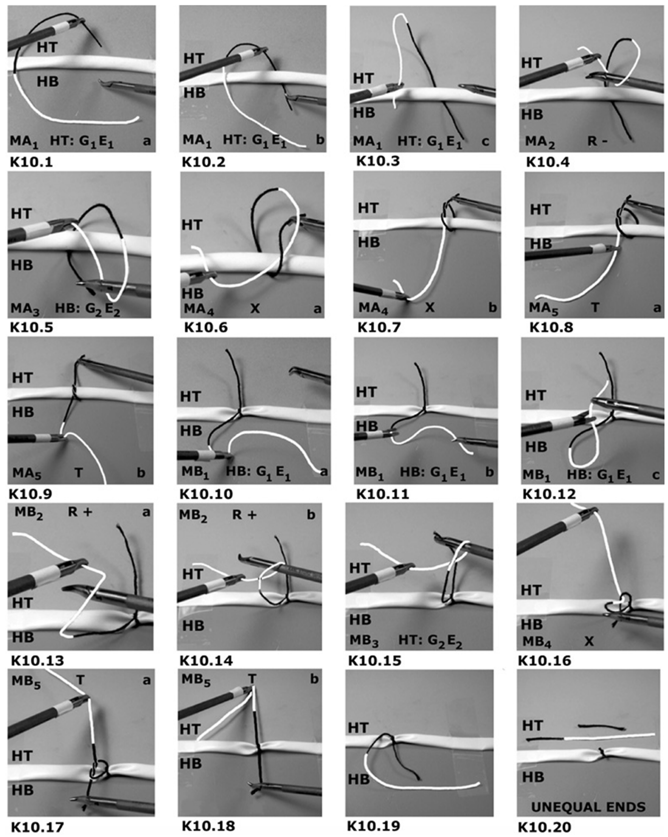


Figure 7. Laparoscopic intracorporeal square knot 10 (unequal lengths–unequal rotations).

Nealon,[1] in his *Fundamental Skills in Surgery* published in 1971, identified and illustrated 3 classic knot-tying techniques: two-hand knot, one-hand knot, and instrument tie. These formed the bases for the open surgery square-knot tying analysis performed in this study.

CONCLUSION

Difficulty mastering LIST is the result of several problems. Poor instrumentation, improper port placement, and the limitations of a 2-dimensional video monitor are all well-know causes. Ignorance of the 16 different methods by which to perform LIST may be a previously unknown factor. If surgeons are not familiar with all the possibilities available to them, they will inevitably end up practicing randomly and confusing different square-knot tying techniques.

Granted, talented surgeons already perform LIST flawlessly. For these individuals, knowledge of the existence of 16 laparoscopic square knots is irrelevant. On the other hand, the rest of us can benefit from this knowledge. Knots K1, K2, K9, and K10 appear to favor RHS and with practice can be tied quickly, without extraneous movements. The ideal knots for LHS have yet to be determined.

Ultimately, the choice must be left up to individual surgeons. One must keep in mind that what works for one surgeon may be entirely different for another. Studying the motions of 16 laparoscopic square knots can be compared to learning a new sport. While practice is essential in mastering any skill, in LIST one must always keep in mind: do not mix up the game rules!

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