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Biomechanical Investigation of the 0° Longitudinal Pull *versus* the 90° Transverse Pull Force on Knot Security

Lin SY[1], McGrouther DA[2,3] and Wong YR[2]*

[1]Yong Loo Lin School of Medicine, National University of Singapore, Singapore

[2]Biomechanics Laboratory, Singapore General Hospital, Singapore

[3]Department of Hand Surgery and Reconstructive Microsurgery, Singapore General Hospital, Singapore

Abstract

Fewer biomechanical studies focused on the intricacies of the suturing steps and techniques and its influence on knot security. This paper aims to develop a biomechanical testing method and evaluate the biomechanical performance of reef knots made by using the 0° longitudinal pull and 90° transverse pull at the last throw.

Forty samples of fresh porcine skin were sutured with either a 0° longitudinal pull (n=20) or a 90° transverse pull (n=20) using Prolene® 4.0 suture. The tying force was standardized at 4 ± 0.5 N and then survival testing on the samples was performed. The medians of the slippage/breakage force and the nth cycles before breakage were tabulated.

The 0° longitudinal pull had a higher survival rate compared to the 90° transverse pull. However, statistical analysis reported no statistically significant difference in between the group of 0° longitudinal pull and 90° transverse pull for the knot strength and the nth cycles before breakage.

The low survival and nth cycles before breakage of the 90° transverse pull could be attributed to the steeper learning curve. It warrants further studies to investigate the effects of different types of suture techniques, suture material and operators of a different skill level.

Keywords: Biomechanical testing; Tying force; Prolene® 4.0; Reef knot; Knot configuration

Introduction

Knot security is defined as the survival of a suture knot afterload has been applied [1,2]. Secure knots are crucial for safe surgical and interventional practice, serving its function in ensuring hemostasis anastomosis, and appropriate apposition of wounds [3]. There is a myriad of techniques used to make a surgical knot. For instance, it is a common practice in surgery to use interrupted sutures and then to add multiple loops (often termed as "throws") in the belief that this will increase the knot security. These throws may be tightened by traction in line with the suture or alternatively it may be twisted at the right angle to the knot. However, it is not clear if the strength of the knot is altered by the line of tension or the frictional force on suture material [4].

The frictional force is proportional to the area of contact which is believed to achieve more secured grip. Intuitively surgeons tighten a knot be either tightening the second throw or twisting the orientation of the second or subsequent throw. The later action appears to improve the knot security by increasing the contact area between the strands through a total 3-dimensional deformation of the knot raising the frictional forces of that throw. Current recommendations advising multiple throws, with the application of at least apply six 'throws' when securing knots of monofilament material, five 'throws' for sliding knots, and three 'throws' for a surgeon's knots [2,5-7]. However, amid enhancing the knot's security by increasing the number of 'throws', it is often easy to forget that such methods would be pointless if the technique for which these knots were formed are inadequate [3,4].

Currently, the most common knot used for surgical procedures is the reef knot. The reef knot is non-sliding knot, which interlocks at both ends, preventing it from slipping. After completing the required number of 'throws', it is common for the surgeon to apply either a 0° longitudinal pull or a 90° transverse pull, to 'lock' the 'throws' (Figure 1A, 1B). This is largely dependent on the surgeon preference and familiarity. The 0° longitudinal pull relies on the tension between the pull of the two strings to 'lock' the 'throws' down, while the 90° transverse pull introduces an additional 'hooking' mechanism to hook both aspects of the string together, increasing the compression between the

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Correspondence:
Wong Yoke Rung, Biomechanics Laboratory, Singapore General Hospital, 20 College Road, Academia, Level 1, 169856, Singapore,
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strings.

To date, fewer biomechanical studies focused on the intricacies of the suturing steps and techniques and its influence on knot security. A recent meta-analysis curated several papers looking into how the type of suture material could influence knot security but the biomechanical performance of the actual techniques used in the formation of the knot on the integrity and security, rather than the type of suture material, type of knot or number of throws is still unknown [8]. The latest study on standard reef knots done by Drabble et al. mainly noted the difference between the application of tension and the significance of crossing hands on the security of reef knots [3]. However, they did not investigate specifically on the technique used. Henceforth, this study aims to determine the biomechanical performance of the 0° longitudinal pull and the 90° transverse pull based on reef knots with specified tying force at the last throw. We hypothesize that the above mentioned 0° longitudinal pull and the 90° transverse pull could affect the knot security and thus contribute to a better understanding of the underlying significance of such techniques.

Methods

All methods were setup and carried out in accordance with relevant guidelines and regulations. All the data and results were reported in accordance with ARRIVE guidelines.

Specimen preparation

Fresh frozen porcine skin was purchased from the butcher shop and used in this experiment. The porcine skin was defrosted to room temperature in 0.9% saline solution. It was then cut to the size of 140 mm × 15 mm, with an incision made in the middle of the porcine skin along the longitudinal direction to simulate an open skin wound. Each side of the porcine skin was measured at 70 mm × 15 mm. Prolene® 4.0 (Ethicon, US) a single stranded synthetic nonabsorbable polypropylene monofilament sutures was used to stitch the skin. For each specimen, 3 throws were made (1-1-1), with the distance of the stitch to the edge of the wound fixed at 5 mm.

We conducted a power analysis to determine the minimum number of samples based on the mean and standard deviation of the groups. For a 2-tailed test with alpha of 0.05% and 80% power, minimum of 16 samples per each group would be required. Therefore, a total of 40 samples were intended, with 20 samples adopting the 0° longitudinal pull, while the remaining 20 samples adopted the 90° transverse pull. The sequence of tying the 2 different knots was randomized in order to eliminate the memory effect of tying a knot. The same operator (first author), a fourth-year medical student tied the knots for all specimens.

Standardizing the tying force

The Instron 3343 (Instron Corp, Carton MA, USA) mechanical tester was used to measure the tying forces, ensuring that the tying force was maintained at 4 ± 0.5 N as seen in Figure 2. Firstly, the suture was looped around the 2 metal bars, first around the bottom bar then looped upwards to the top bar with a controlled downward force. Based on the force equilibrium, both upwards and downward tension of the suture gave a resultant force which is measured by the mechanical tester. Only the final throw was measured, since making a simple cross suture of the first two throws without any taut would not warrant a stable enough force to measure.

Survival testing

Survival testing was then performed at room temperature on the E-1000 Dynamic Tester (Instron Corp, Canton MA, USA). The ends of the porcine skin were mounted on to the pneumatic grippers with blasted clamping surfaces. The distance between the two grippers were maintained in such a way that the specimen would not taut as seen in Figure 3. As per studies done by Lim et al. and Matheson et al., survival testing protocol was adopted to evaluate the biomechanical performance of the knot. The test was started at stage 1 with 2 N-10 N (minimum-maximum loading) for 200 cycles at 1 Hz. Thereafter, the maximum loading was increased by 10 N for each survived stage until failure [7,8]. Both knot slippage or suture breakage was considered as failure criteria for the test. The results of the individual samples were then recorded and labelled with numbers 1 to 20 in the order which they were made.

Statistical analysis

The median of the slippage or breakage force and the nth cycles before breakage survived were tabulated and compared amongst the groups based on statistical analysis. Non-parametric Mann-Whitney U Test was utilized to compute the statistically significant difference in between groups. A p-value smaller than 0.05 is considered significant difference. The failure of specimens was analyzed under the microscope and recorded by photographing.

Results

Table 1 shows the survival of all specimens with respect to their strength and n^{th} cycle of failure. There was one knot slippage noted in the 90° transverse pull group. It was considered as an outlier and omitted from the subsequent analysis because no abnormal observation was made on this sample.

The 0° longitudinal pull had a higher survival rate compared to the 90° transverse pull (Stage 1: 85% *vs.* 80%, Stage 2: 65% *vs.* 40%). As shown in Figure 4, no statistically significant difference was found in between the strength for the 0° longitudinal pull and the 90° transverse pull (21.8N *vs.* 20.0, p=0.258). As shown in Figure 5, there is also no significant difference in the n^{th} cycles before breakage survived when comparing between the 0° longitudinal pull and the 90° transverse pull (436 cycles *vs.* 209 cycles, p=0.120).

Table 1 shows that one knot slippage was noted on a sample of the 90° transverse pull group, while the rest of the knots failed due to knot breakage. For the knots that failed by breakage, further analysis of the

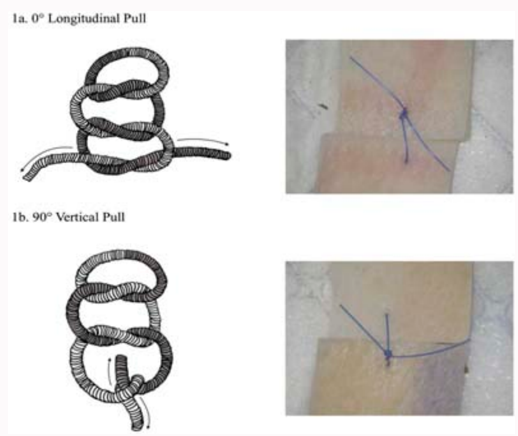

Figure 1: A and b) Illustrative and microscopic comparison of the knot configurations between the 0° longitudinal pull and the 90° transverse pull.

Table 1: Results of survival testing for 0° longitudinal pull and 90° transverse pull.

	Breaking strength (N) (Number of Stages Survived Before Knot Failure)	n^{th} cycle before failure
0° Longitudinal Pull		
1	22.1 (2)	444
2	26.0 (2)	400
3	22.5 (2)	458
4	22.3 (2)	465
5	17.0 (1)	203
6	22.8 (1)	207
7	22.6 (2)	447
8	23.4 (2)	446
9	17.9 (1)	205
10	23.6 (2)	447
11	17.5 (0)	10
12	19.5 (0)	10
13	21.3 (2)	438
14	17.9 (0)	3
15	23.6 (2)	452
16	20.4 (2)	434
17	24.3 (2)	445
18	21.0 (1)	208
19	21.5 (2)	442
20	19.4 (2)	428
Median	**21.8**	**436**
90° Transverse Pull		
1	22.2 (1)	201
2	18.8 (1)	201
3	20.5 (0)	154
4	19.6 (1)	209
5	19.4 (2)	432
6	6.5 (0)*	0*
7	20.5 (1)	205
8	17.7 (1)	208
9	23.2 (2)	455
10	17.2 (1)	208
11	20.1 (0)	4
12	20.7 (1)	209
13	19.5 (1)	204
14	16.3 (0)	3
15	25.7 (2)	443
16	19.2 (1)	427
17	22.3 (2)	447
18	19.8 (2)	421
19	24.5 (2)	401
20	22.7 (2)	433
Median	**19.95**	**208.5**

*Knot slippage noted

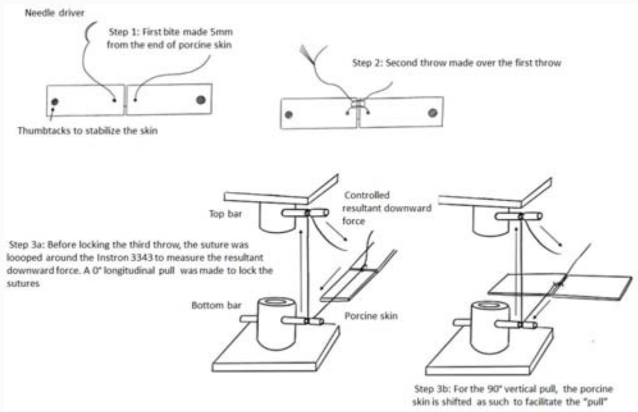

Figure 2: Steps to measuring the tying force.

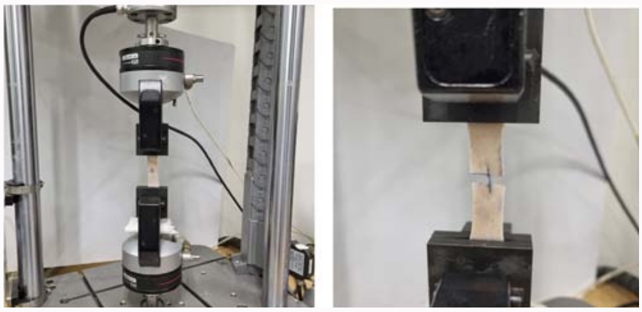

Figure 3: Placement of the specimen for survival testing.

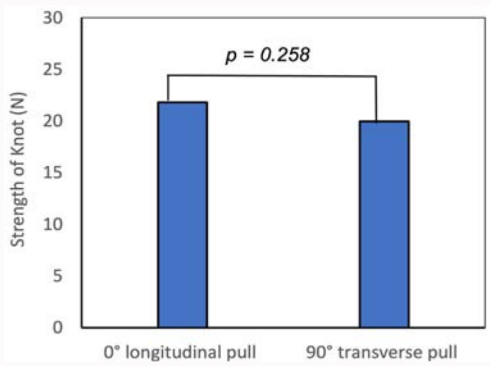

Figure 4: Strength of knots.

breakage showed that the suture breakage took place along or at the knot itself as seen in Figure 6.

Discussion

The formation of a secure knot remains a vital part of a surgeon's craftmanship. The ability to tie a reliable and secure knot has always been an essential skill, even with the advent of new technological advances [3]. The reef knot, despite being used for many centuries has stood the test of time to become one of the most common knots used today, forming the basic configuration of more complicated knots such as the surgeon's knot [9,10]. The reef knot relies on equal amount of frictional strength on both strands to hold the knot together, thus the force applied when locking the knots play a critical role in its security [4]. Unequal application of force on either working end could change its 3-dimensional deformation of suture, in turn resulting in knot failure [11]. In this study, we developed a method

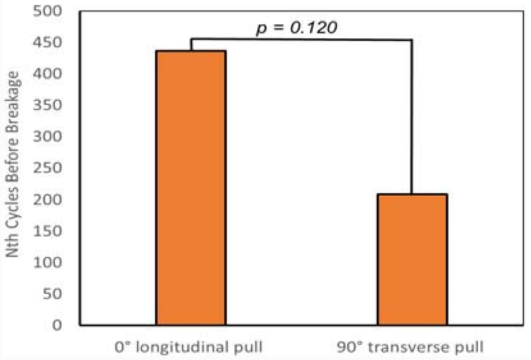

Figure 5: n^{th} cycle before breakage distribution.

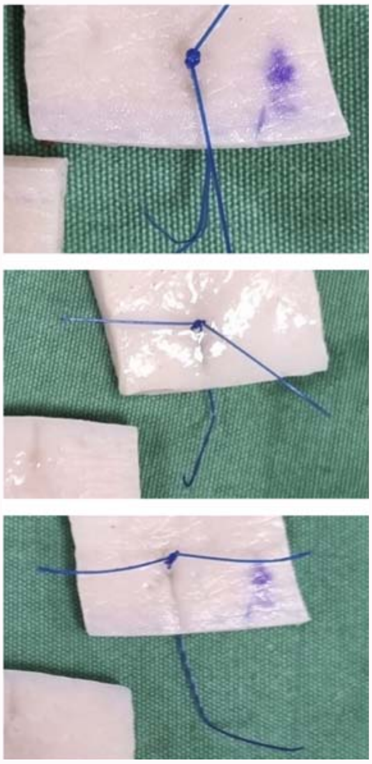

Figure 6: Failure at knot or along knot.

to standardize the tying force when locking the last throw so that an equal force could be applied. In our study, the tying force of the last throw was fixed at 4 ± 0.5 N since it has been proven to produce the highest knot survival rates [12].

Table 1 shows that the survival rate for the 0° longitudinal pull was higher as compared to the 90° transverse pull (Stage 1: 85% *vs.* 80%, Stage 2: 65% *vs.* 40%). Based on the order of samples shown in Table 1, we noticed that the number of knots surviving for the 90° transverse pull group was increasing at stage 2 over time. Unlike the first 5 samples (labelled 1-5) made for which none of these samples survived stage 2, the last five samples made (labelled 15-20) survived till stage 2. Whereas for the 0° longitudinal pull, the number of knots that failed at Stage 2 were evenly distributed across the 20 samples. Since the operator for both groups remained the same, this highlights the possibility of a steeper learning curve for the 90° transverse pull compared to the 0° longitudinal pull. Thereby, resulting in poorer results for the 90° transverse pull initially, which may influence the

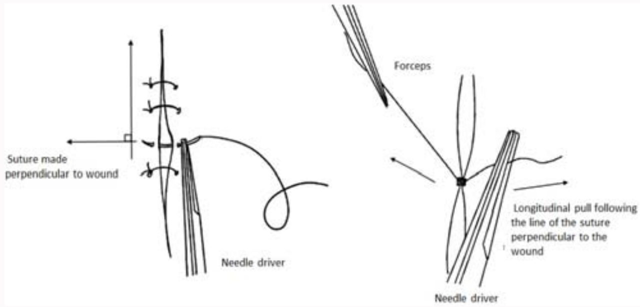

Figure 7: Suture direction in relation to wound.

overall survival rate. As for the reason behind the discrepancy between the learning curve of the 90° transverse pull and 0° longitudinal pull, the answers may lie in the direction for which sutures are placed in relation the wound.

In majority of surgical wounds, the direction in which the suture placed is often perpendicular to the wound itself. This is especially in the case of a simple interrupted suture, a common suturing technique used to close incisional wounds. With the direction of the suture being perpendicular to the incision, it is more intuitive to do a 0° longitudinal pull following the direction of the suture, compared to a 90° transverse pull, which follows the direction of the wound instead of the suture, as seen in Figure 7. Thus, making the 0° longitudinal pulls a more intuitive and easier method to master. However, this can be easily overcome with practice. Several studies involving medical students and residents have shown that most participants demonstrated better results with practice, even with more advanced techniques, such as laparoscopic suturing which require greater hand-eye co-ordination [13-15]. Thus, we advocate that the survival rate of both the 0° longitudinal pull compared to a 90° transverse pull groups is similar in between the two configurations after sufficient practice of the surgeon.

It was also notable that none of the samples survived through the stage 3. As shown in Table 1, the median of knot strength for 0° longitudinal pull and 90° transverse pull are 21.8 N and 19.95 N, mostly without slippage. We postulate that the mechanical strength of the suture of the Prolene® suture limits the maximum knot strength which is unable to withstand this force and thus resulting in the breakage of the suture knot. In the future, a stronger suture material, such as Fiberwire® can be used or higher number of throws can be made for the reef knot based on Prolene® suture to investigate the effect of mechanical property of suture material.

There are several limitations in our study. Although porcine skin is widely used in suturing studies, it is unable to perfectly mimic the nature of human skin. Given that the texture and tension of the skin can vary with different regions of the body, the results may differ on human skin. A future cadaveric model should be used for more translatable results. On the other hand, such results are only applicable in the case of simple interrupted sutures made using the Prolene® 4-0 suture material. Thus, these results may change if a different suture material, suturing technique or operator of a different surgical skill level was utilized. Further studies are required to investigate whether these other factors may result in a significant difference between the 90° transverse pull and 0° longitudinal pull technique.

Conclusion

This study revealed the breaking forces and the n^{th} cycles before breakage can be achieved by the 0° longitudinal pull and 90° transverse pull based on Prolene® 4.0 suture material. No statistically significant difference was found in between the groups. It was notable a higher survival rate in the 0° longitudinal pull technique as compared to the 90° transverse pull technique. This could be possibly attributed to the steeper learning curve required for the 90° transverse pull technique. Based on the results obtained in this study, it warrants further studies to investigate if this hypothesis holds true for different types of suture techniques, suture material and operators of a different skill level. Further cadaveric studies can be done across different types of tissues to allow for this study to be more translatable to a surgical setting.

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