Effect of Tying Conditions on the Knot Security of Suture Materials

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ABSTRACT: Although the knot security of suture materials has been widely investigated, there are few reports on the effects of knot tying conditions. With respect to foreign body reaction, it is preferable to use the minimum possible amount of suture materials and to use an appropriate material to ensure knot security. In this study, the different effects of knot tying conditions, such as knot type, tying force, and tying speed, were investigated. Knot tying was performed by a tensile tester for reproducible testing with the least amount of hand tying variation. The square knot (1 = 1 = 1) was shown to be the most appropriate knot type to evaluate monofilament sutures with a tensile tester. Increasing the tying speed and tying force enhanced knot security. The mechanical tying method was found to be a useful alternative to hand tying and provided reproducible test results. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 918–922, 2008

Key words: fibers; strength

INTRODUCTION

Suturing materials are used for conjoining adjacent tissues and for ligating blood vessels. Such applications require knots to be tied so that a secure suture loop is formed. A commonly used method to increase knot security is an additional throw.[1–5] This method, however, increases suture volume and may increase foreign body reactions[6,7] because not only must the knot stay tied but also the amount of material must be kept to a minimum to reduce adverse reactions. Surgical knots are a very important aspect of surgical technique and clinical performance, and knot tying takes up a substantial portion of total operation time.[8] Monofilament sutures have various advantages over multifilament ones, including low tissue drag, low capillarity, and a smooth surface. However, knot security is a greater concern with synthetic monofilament sutures because of a lower friction coefficient compared with that of multifilament sutures.

Despite knot security importance, there have been few reports that evaluate tying conditions. The effects of tying methods, including tying force and type, have previously been reported. However, results are difficult to reproduce, and the tying methods have been obscure. For example, in those studies, hand tying was usually performed, and the force was described in terms of ''maximum hand force'' or ''moderate force.''[1,2,6,8] In addition, tying speed, a critical parameter, has been largely ignored.[9–14] To be used as a standard method for knot security, a test method should show the discrimination of test results between the sutures and reproducibility. In this study, the effect of tying methods on knot security was investigated, and a standardized test for measuring knot security was established.

EXPERIMENTAL

Materials

PDSII (polydioxanone from Ethicon, Somerville, NJ), Maxon (a copolymer of glycolide and trimethylene carbonate from Tyco, Mansfield, MA), and Monocryl (a copolymer of glycolide and caprolactone from Ethicon) were purchased. A sea/island-type bicomponent monofilament suture (i.e., MonoFlex, Daejeon, Korea), composed of polydioxanone and poly(*p*-dioxanone-*co*-trimethylene carbonate-*co*-ε-caprolactone), was prepared as previously described.[14,15] This sea/island-type suture contains many fine strands (sea component, 70 vol %) of a polydioxanone within a matrix (island component, 30 vol %)

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TABLE I
Definitions of Terms Used in This Study

Term	Unit	Definition
Knot failure		Slippage or breakage of tied knot
KS	%	Ratio of the number of knots slipped to the total number of knots tied
KPS	kgf	Force when knot breakage happens
EP KPS	kgf	Knot pull strength described in European Pharmacopoeia (USP 1, 5.2 kgf; USP 2/0, 2.7 kgf)
KHC	kgf	Force when knot failure happens
Secure knot		Knot for which the knot slippage ratio is less than 10%

of poly(*p*-dioxanone-*co*-trimethylene carbonate-*co*-ε-caprolactone).

Testing methods

A tensile test machine (H5K-T, Hounsfield) was used to tie and evaluate knot security. A polyethylene bottle with a 5-cm diameter was used as a mandrel. The knot pull strength (KPS) was described as the strength from the physician's perspective, and the knot holding capacity (KHC) was described as the strength from the patient's perspective. Definitions used in this study are listed in Table I.

Knot tying by a mechanical method or by hand

Monofilament suture samples were wound around the mandrel (first throw), and a second throw (2 = 1, 1 = 1, or 1 × 1) was added. One ear was secured to the upper jaw of the tensile tester, and the other was attached to the lower jaw with a distance of 60 mm. Knot tying was performed by upward movement of the upper jaw at a predetermined extension rate. The load, equivalent to the predetermined tension for tying a knot, was maintained for 5 s before knots were detached. After detachment, an additional throw was applied (2 = 1 = 1, 1 = 1 = 1, or 1 × 1 × 1), and the same procedure was repeated 10 times. No tension was applied to the patient side of the knot during tying. Ears were cut to 2–3 mm, and the loop was divided at the mid-portion by the cutting of the suture loop at the opposite site or the knot on the mandrel.

On the other hand, surgeon's knots (2 = 1 = 1) were made by the skilled knot tier using the same mandrel used in mechanical tying. All tests were performed by the same skilled knot tier to diminish variability and repeated 10 times.

Knot security measurement

Knotted sutures, the divided ends of the loop, were placed on a tensile tester and pulled apart until knot failure occurred by knot breakage or slippage. The sample gauge length was 50 mm, and the extension speed was 50 mm/min. The knot slippage ratio (KS) and KHC were averaged over 10 measurements to determine the knot holding strength from the patient side. The knot breaking load was taken as the maximum load value on the load–extension curve before knot failure (ASTM D 2256-69).

Morphology

Images of knot configuration were taken by field emission scanning electron microscopy (JSM6335F, JEOL, Tokyo, Japan).

RESULTS AND DISCUSSION

Effect of the knot configuration (knot type)

To evaluate the effect of knot configuration, MonoFlex [United States Pharmacopoeia (USP) 1] was tested with a mechanical tying method. The knot tying speed was 500 mm/min, and the tying force was 2.0 kgf. Surgeon's (2 = 1 = 1), square (1 = 1 = 1), and granny (1 × 1 × 1) knots were selected to evaluate the effect of knot configuration on knot security. The square knot (1 = 1 = 1) showed excellent knot security and reproducibility, and unexpectedly, the surgeon's knot showed poor knot security. In general, it is well known that the surgeon's (2 = 1 = 1) and square (1 = 1 = 1) knots are more secure than the granny knot (1 × 1 × 1).[2–4,6,8,9] A knot with a symmetric structure during knot formation has better knot security. In the surgeon's knot (2 = 1 = 1), a symmetric structure is formed by hand tying,

TABLE II
Effect of the Knot Type on Knot Security with Mechanical Knot Tying

	Surgeon's knot (2 = 1 = 1)		Square knot (1 = 1 = 1)		Granny knot (1 × 1 × 1)	
	KS (%)	KHC (kgf)	KS (%)	KHC (kgf)	KS (%)	KHC (kgf)
First test	60	4.2 ± 0.2	0	5.2 ± 0.5	20	4.7 ± 0.6
Second test	40	4.7 ± 1.2	0	5.7 ± 0.4	20	5.4 ± 0.8

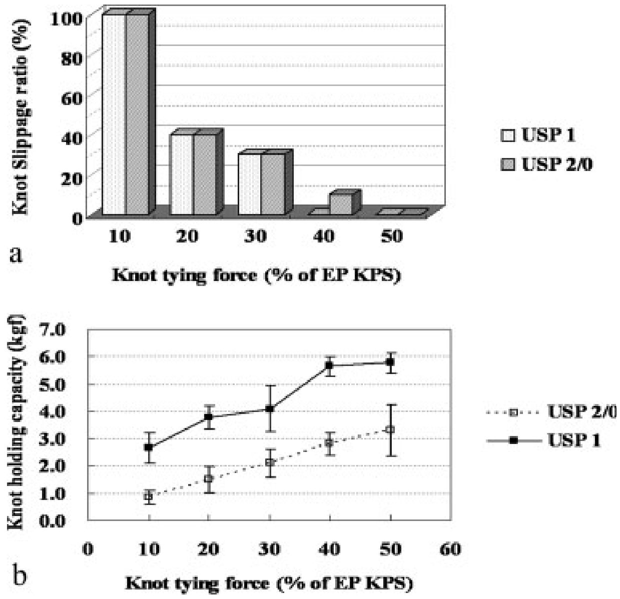

Figure 1 Effect of the knot tying force on (a) KS and (b) KHC of MonoFlex.

but in this study, surgeon's knots had asymmetry when tied by a tensile tester. Trimbos[2] proposed that this asymmetry results in different friction coefficients of the two threads, which decrease KHC. On the contrary, the square knot (1 = 1 = 1) had a symmetric structure when formed by the tensile tester. Thus, it was confirmed that the square knot (1 = 1 = 1) was the most appropriate for evaluating knot security made by a tensile tester (Table II).

Effect of the knot tying force

We next investigated the effect of knot tying force on knot security of MonoFlex (USP 1 and 2/0) using a square knot (1 = 1 = 1). Both the USP 1 size (diameter, 0.518 mm) and the USP 2/0 size (diameter, 0.370 mm) were established by UPS. Knot tying was performed by a tensile tester with a tying speed of 500 mm/min, and the tying force was selected on the basis of European Pharmacopoeia (EP) KPS. KS decreased, and KHC increased with an increase in the tying force (Fig. 1). These results indicate that knot security can vary, depending on the tying force. However, a constant tying force is performed by a tensile tester and can provide reproducible results. When slippage is less than 10%, the knot is considered to be secure.[9,10] In the case of MonoFlex, secure knots were obtained when the tying force was greater than 40% of EP KPS. Figure 2 shows the knot configurations of MonoFlex (USP 1) with different tying forces. An increase in the tying force resulted in a void decrease between suture filaments.

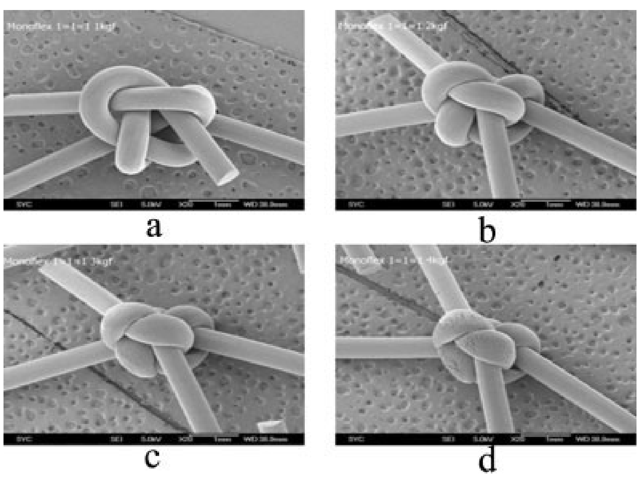

Figure 2 Knot configuration of MonoFlex (USP 1) with different tying forces: (a) 20%, (b) 40%, (c) 60%, and (d) 80% of EP KPS (the original pictures were taken at 20× magnification).

Effect of the knot tying speed

To evaluate the effect of knot tying speed on knot security, a square knot (1 = 1 = 1) formed by mechanical tying with MonoFlex (USP 1 and USP 2/0) with a tying force of 40% of EP KPS (2.1 kgf for USP 1 and 1.1 kgf for USP 2/0) was used. Tying speed influenced the security of MonoFlex (Fig. 3). KS decreased and KHC increased with increased tying speed. These results can be attributed to the force on the knot increasing with increased tying speed because of decreased impact time. Excellent knot security was obtained at a speed of 500 mm/min.

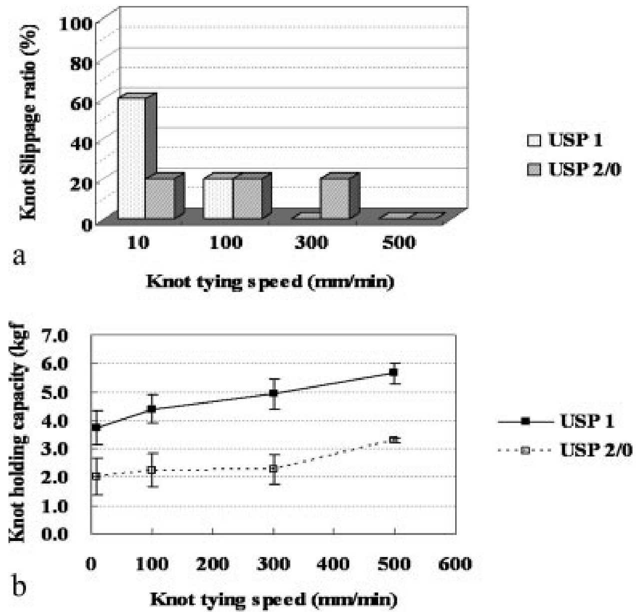

Figure 3 Effect of the knot tying speed on (a) KS and (b) KHC of MonoFlex.

Comparison between hand tying and mechanical tying

It is important to use mechanical tying when knot security is being tested. To evaluate discrimination ability in this study, MonoFlex and commercialized monofilament sutures (PDSII, Maxon, and Monocryl) were tested and compared with conventional hand tying and mechanical tying. For hand tying, a surgeon's knot (2 = 1 = 1) with a knot tying force of 1.5–2.0 kgf was used because the surgeon's knot is known as one of the secure knots for monofilament sutures.[1,4,5] For mechanical ties, square knots with a force of 40% of EP KPS and a speed of 500 mm/min were used.

A strong correlation was observed between hand and mechanical tying with the various suture materials tested (Fig. 4). Figure 5 shows constructed knot configurations formed by mechanical tying. Configurations varied by suture materials, even when a similar force was applied (2 kgf). MonoFlex showed a tight knot configuration, and a hill and valley morphology was observed on the knotted surface [Fig. 5(a)]. On the contrary, Monocryl showed a loose knot structure [Fig. 5(c)]. PDSII appeared to be tied more firmly than Monocryl, but a hill and valley morphology was not observed, and this may explain differences in the knot security of the sutures used in this study. The surface deformation (e.g., hill and valley) increases the frictional coefficient of suture materials and enhances security. These results imply that mechanical tying can be a useful method to evaluate knot security and could replace the use of hand tying in these kinds of studies.

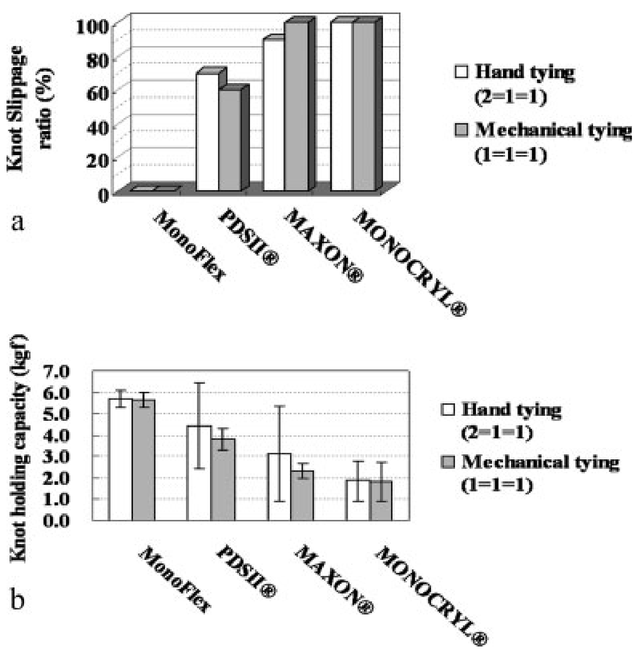

Figure 4 Comparison of mechanical and hand tying methods: (a) KS and (b) KHC of various suture materials.

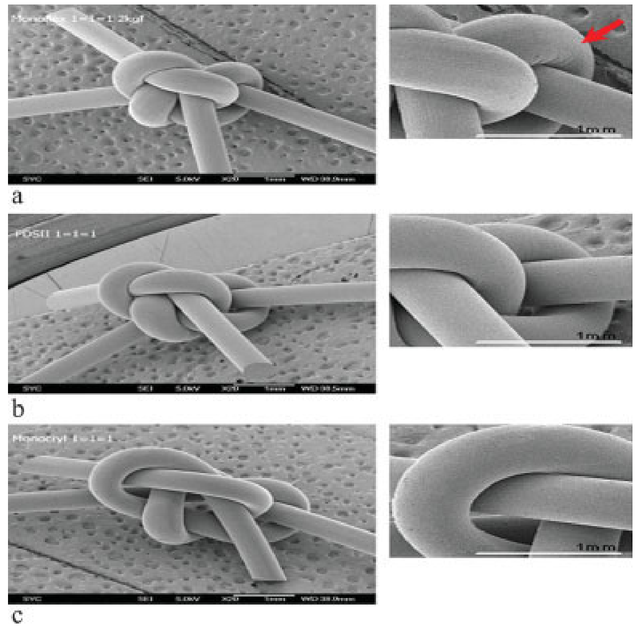

Figure 5 Knot configurations of (a) MonoFlex, (b) PDSII, and (c) Monocryl. An arrow indicates the hill and valley on the surface of the monofilament suture (the original pictures were taken at 20× magnification). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

CONCLUSIONS

Mechanical tying was adapted to be used instead of hand tying and to establish a reproducible testing method for knot security evaluation. Knot security was improved with increasing tying force and tying speed. The most efficient knot for evaluating security was the square knot (1 = 1 = 1), which was formed by mechanical knot tying with a tying force of 40% of EP KPS and a tying speed of 500 mm/min. The mechanical tying method can diminish the variation caused by the hand tying method and provide practical insight into the knot performance of surgical suture materials.

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