

МЕХАНИЧНО ПОВЕДЕНИЕ НА ПЛЕТЕНИ СИНТЕТИЧНИ ХИРУРГИЧНИ КОНЦИ

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MECHANICAL BEHAVIOUR OF BRAIDED SYNTHETIC SU- TURES

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Abstract:

The success of a surgical suture is largely determined by its mechanical properties, particularly tensile strength and resistance to knot slippage. However, the evaluation of suture tensile behavior remains challenging due to the lack of a standardized international testing method. This study presents an experimental approach for assessing the mechanical characteristics and knot slippage of braided polyester fiber sutures. The influence of braid angle on both tensile performance and knot behavior was investigated, and a slippage ratio derived from load-extension curves was introduced. Results showed that braid angle significantly affects the breaking load and elongation of the sutures. The presence of a knot reduced the breaking load, with failure consistently occurring in the knot region. Furthermore, the proposed slippage ratio provided an effective means of comparing the slippage resistance of different knot configurations.

Keywords: braided suture, tensile performance, knot slippage, slippage ratio, braid angle.

INTRODUCTION

Suture materials have been used for wound closure for over 4,000 years, from ancient Egyptian linen threads and animal sinews to modern natural or synthetic, absorbable or non-absorbable sutures. Absorbable sutures degrade in the body during healing, while non-absorbable sutures resist degradation and may require removal. Natural absorbable materials include silk, collagen, and catgut, whereas synthetic sutures are commonly made from nylon, polyester, and glycolide-based polymers.

Suture fibres must be biocompatible and mechanically reliable. Although silk has been widely used, it exhibits limited tensile strength and may provoke tissue reactions. In contrast, polyester polyethylene terephthalate (PET) offers excellent biocompatibility and strength, making it suitable for vascular prostheses and artificial ligaments [1–3]. Natural absorbable sutures often show poor long-term strength retention, while synthetic absorbable glycolide-based sutures generally perform better but may degrade faster after gamma sterilization.

Sutures are available as monofilament or braided structures. Monofilaments have smooth surfaces but may suffer from knot slippage and handling difficulties. Braided sutures provide greater flexibility and knot security, although they may be more susceptible to infection and mechanical damage [1]. Since knot stability depends largely on friction within the knot, some degree of slippage is unavoidable. Increasing the number of throws can reduce slippage, but it prolongs surgery and may increase contamination risk [4].

Previous studies have focused on knot security, loop security, and cyclic loading performance of various suture materials [5–10], as well as the effect of throw number on knot resistance to untying [11,12]. However, the influence of braided suture structure on knot slippage remains insufficiently explored, despite its importance for surgical outcomes and infection prevention.

An ideal suture should combine biocompatibility, adequate tensile strength, good knot security, elasticity, fatigue resistance, minimal tissue reaction, and ease of sterilization. Suture security depends on factors such as friction, strand diameter, structure, stiffness, and knot configuration [4]. Failure may occur through knot rupture or progressive knot untying caused by slippage.

The aim of this study is to develop a novel method for quantifying knot slippage in braided sutures and to investigate how structural parameters, particularly braid angle and knot type, affect the mechanical behaviour and slippage performance of knotted and unknotted sutures.

MATERIAL AND METHODS

Circular braided sutures were manufactured using sixteen non-texturized polyethylene terephthalate (PET) multifilament yarns of 100 dtex on a HER-ZOG circular braiding machine, typically employed for the production of simple and core-braided structures (Figure 1). Preliminary trials conducted with textured polyester yarns revealed that the resulting braided structures exhibited excessive elasticity, rendering them unsuitable for surgical suturing applications.



Figure 1. Braiding machine

A regular 1/1 braid architecture was produced using a 16-carrier circular braiding machine. The sequential movement of the carriers enabled the interlacing of the sixteen yarns to form a simple tubular braid. Three different braid configurations were subsequently fabricated by varying the take-up speed through adjustment of the machine cogwheel ratio while maintaining all other manufacturing parameters constant.

The braid angle is one of the most important geometric parameters characterizing a braided structure. Variations in braid angle significantly affect both the diameter and the mechanical behavior of the braid [13]. The braid angle, denoted by θ , is defined as half the angle formed by two interlacing yarns within the braided structure. It is directly related to the take-up speed, which in turn depends on the cogwheel ratio of the braiding machine.

The braid angle was determined from digital images acquired using an optical microscope equipped with a digital camera. Image analysis was performed using custom-developed software written in Microsoft Visual Basic 6.0. The procedure consisted of defining two lines (L1 and L2) parallel to the axes of two interlaced yarns by selecting two points on each filament. The equations of the two lines were then calculated and their intersection determined. The braid angle was subsequently obtained as one-half of the angle formed by these two lines (Figure 2).

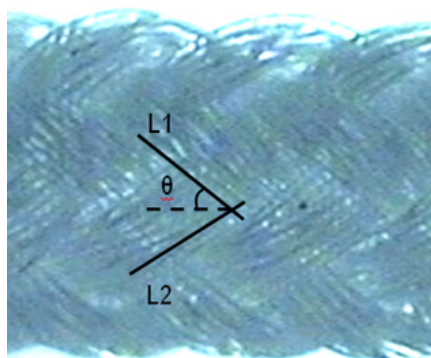


Figure 2. Determination of braid angle by image processing

Load-extension curves of both knotted and unknotted sutures were obtained using a LLOYD LRX 2.5 K universal testing machine operating at a constant crosshead speed, with an initial gauge length of 150 mm (Figure 3). To date, no internationally accepted standard specifies the testing conditions for evaluating the tensile properties of surgical sutures. Therefore, the testing parameters were selected according to ASTM D2101-82, the American standard method for tensile testing of textile yarns. Based on this standard, a constant extension rate of 90 mm/min was adopted, corresponding to approximately 60% of the gauge length. The selected gauge length of 150 mm is also recommended in the INSTRON® technical application report for straight-pull and knot-pull testing of surgical sutures [14] and has previously been used by Hong et al. [15] in the evaluation of monofilament sutures. All specimens were tested under identical gauge-length conditions to ensure meaningful comparisons between different suture structures and knot configurations.

During testing, each specimen was clamped between the grips of the tensile testing machine and subjected to uniaxial tensile loading until failure. Two knot configurations commonly employed in dermatological surgery were investigated: the square knot and the surgeon's knot. For knotted specimens, each suture was tied around a rubber tube with a diameter of 6 mm to ensure reproducible knot formation. Schematic representations of the two knot types are presented in Figure 4. The knot was positioned approximately midway between the two grips during testing.

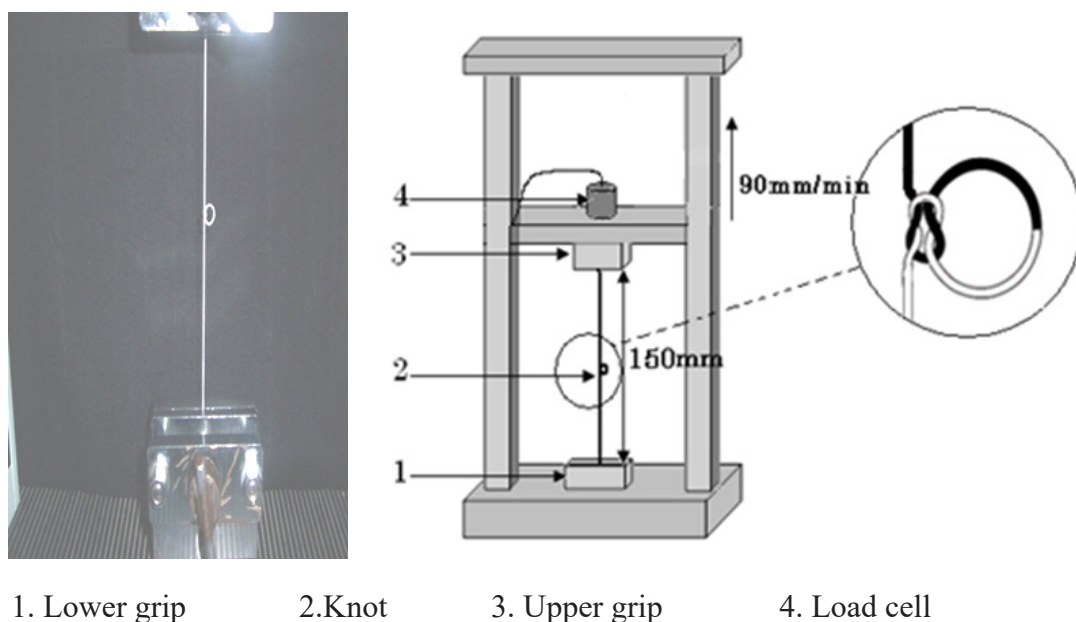


Figure 3. Testing device for suture load-extension measurements.

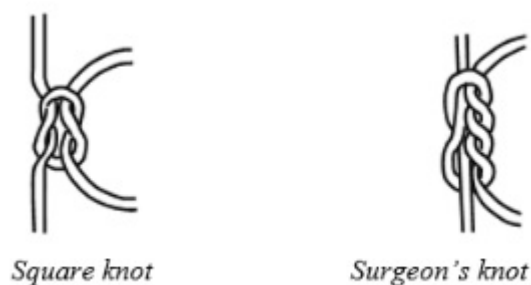


Figure 4. Knot types used for the suture

SR : Slippage ratio (%)

E_K : Knotted suture extension (mm)

E_N : Non-knotted suture extension (mm)

L_I : Initial length of the tested sample (mm)

All tests were performed under testing conditions of 21°C ± 1°C, and 65% ± 2% relative humidity. Ten specimen of each suture were tested.

To evaluate knot-slippage behavior, load-extension curves obtained for knotted sutures were compared with those of corresponding unknotted specimens. A slippage ratio was then calculated at different load levels according to the following relationship:

$$S_R (\%) = \frac{(E_K - E_N)}{L_I} \cdot 100$$

RESULTS

The braid angles (θ) corresponding to the different cogwheel ratios are summarized in Table 1. The re-

sults indicate a clear decrease in braid angle with increasing cogwheel ratio. The variability of the measurements was low, with the coefficient of variation remaining below 2.5% for all samples.

Table 1. Cogwheel ratios and corresponding average braid angles.

Cogwheel ratio	Average braid angle (Degree)	Coefficient of variation (%)
0,163	35,1	2,45
0,179	32,9	2,43
0,196	29,4	1,67

Figure 5 presents the load-extension curves of braided sutures manufactured with different braid angles. An initial quasi-elastic region can be observed up to

approximately 20-30 mm of extension, followed by a plastic deformation region

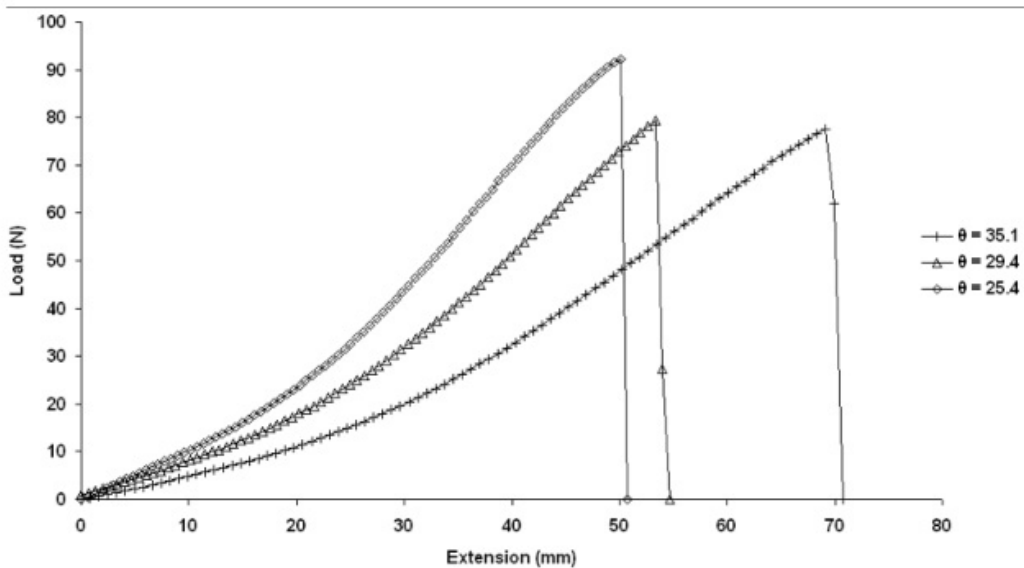


Figure 5. Load-extension curves of non-knotted sutures at 3 different braid angles.

The results also show that increasing the braid angle leads to a reduction in the breaking load while substantially increasing the elongation at break. Tensile tests further revealed that failure consistently occurred in the knot region.

Figure 6 compares the load-extension curves of two knotted sutures and one unknotted suture with a braid angle of 35.1°. It can be observed that knotted sutures fail at significantly lower loads than the corresponding unknotted suture.

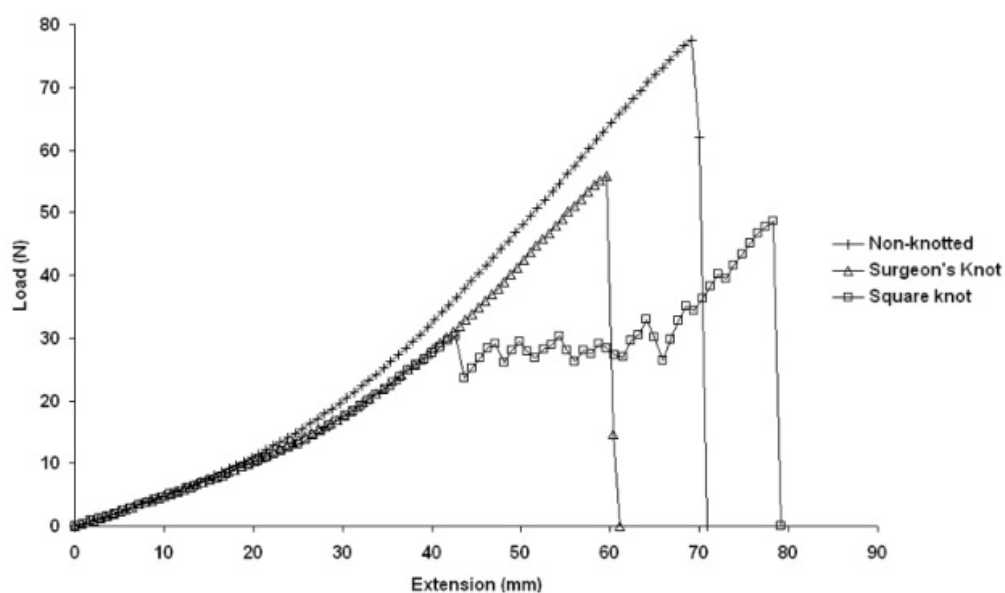


Figure 6. Load-extension curves of knotted and non-knotted sutures ($\theta = 35.1^\circ$).

The relationship between slippage ratio and applied load for square knots and surgeon's knots at three different braid-angle levels is illustrated in Figure 7. For both knot configurations, the slippage

ratio increases with increasing load. In addition, the highest slippage values were observed in sutures with the lowest braid angles.

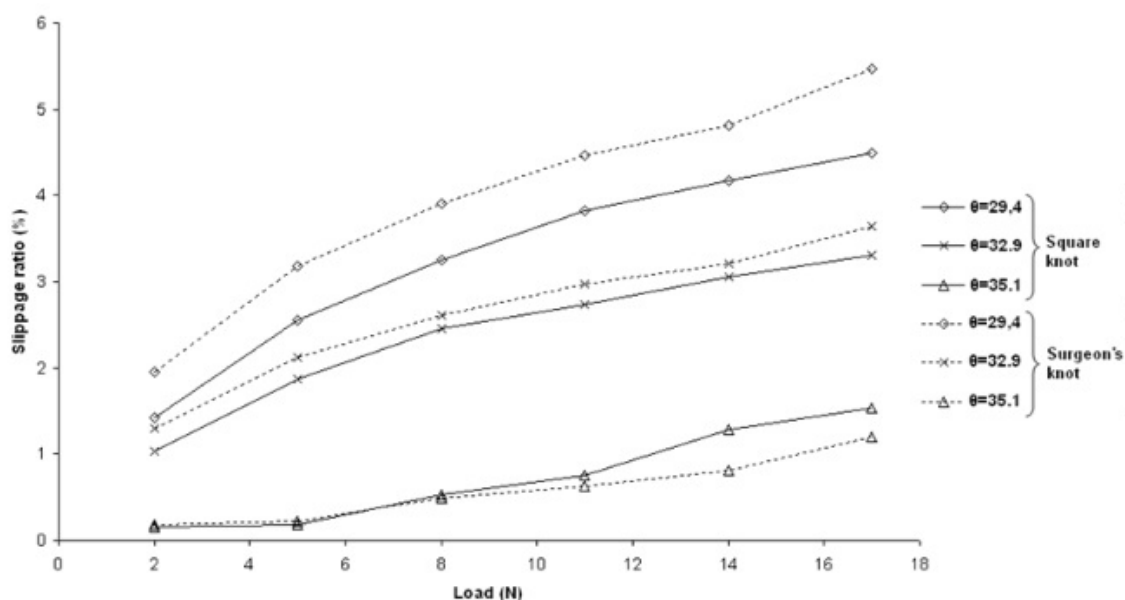


Figure 7. Relationship between slippage ratio and load.

DISCUSSION

The primary objective of this study was to examine the effect of braid angle, a key structural parameter of braided sutures, on their mechanical performance. Experimental results showed that braid angle decreases as take-up speed increases. Braids with larger angles exhibited greater extensibility because the helically arranged yarns undergo significant geometric reorientation and compaction before carrying the applied load. Once the structure reaches a jammed state, the mechanical response is governed mainly by the tensile properties of the constituent yarns. Similar behavior has been reported for circular hybrid braids by Hristov et al. [13]. An increase in braid angle was also associated with a reduction in breaking load. This can be explained by the longer yarn path within high-angle braids, which increases the effective yarn length and the likelihood of defects influencing strength [16].

Comparison of load-extension curves for knotted and unknotted sutures showed that knotting reduced the breaking load for both knot configurations. Failure consistently occurred at the knot rather than along the free suture length, indicating significant stress concentration within the knot region. Similar observations have been reported for monofilament sutures and other ligature structures [17,18]. Stress concentration, structural damage during knot tying, and frictional interactions between yarns are possible contributors to knot failure. The results demonstrated that knot slippage decreases with increasing braid angle. Higher braid angles increase yarn inclination and internal friction, thereby improving knot stability. In contrast, low-angle braids have yarns that are more parallel to the braid axis, generating lower friction and promoting slippage. Consequently, braid angle was found to be a major factor governing knot security.

The proposed slippage-ratio method provided a quantitative means of evaluating knot stability, complementing traditional assessments based solely on knot breaking strength. Results showed that surgeon's knots generally exhibited greater slippage than square knots, particularly in braids with low braid angles. This difference was attributed to the

higher flexibility of low-angle braids, which allows more effective tightening of square knots. As braid angle and stiffness increase, the differences in slippage behavior between the two knot types become less pronounced.

Overall, the study demonstrates that both braid angle and knot configuration significantly influence knot security and mechanical performance. The proposed methodology may serve as a useful tool for optimizing braided suture design and selecting appropriate knot configurations for improved clinical performance.

CONCLUSION

In the present work, we analyzed the mechanical behavior of knotted and non-knotted braided suture made of polyester multifilament yarns. The braid angle has an important influence on breaking load and elongation of the suture. The presence of a knot lowers breaking load and rupture occurs always at the knot region. There is a lack in the published literature concerning the effect of structural parameters of a braided suture on its mechanical properties. Only a few studies examined tensile performances of monofilament suture under different test conditions because of the absence of an international standard test method on this matter. Some properties of suture structure and knots should be known to a surgeon when selecting a suture. We proposed a practical experimental procedure for the measurement of knot slippage based on the determination of load-extension curves.

Further work will focus on the study of the influence of braid angle on braid flexibility which is a fundamental property needed during knotting operation. It would be also useful to study the phenomenon of suture dimensions recovery after elongation. In fact, an unrecoverable elongation of the suture loop obtained following an oedema generates usually an unsightly scar.

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