Knee Surg Sports Traumatol Arthrosc (2014) 22:2849–2855
DOI 10.1007/s00167-013-2452-9

EXPERIMENTAL STUDY

Surgical knot tightening: how much pull is necessary?

Stefan Neuhofer · Karl Wieser · Georg Lajtai · Daniel Müller · Christian Gerber · Dominik C. Meyer

Received: 18 September 2012 / Accepted: 18 February 2013 / Published online: 14 March 2013

Abstract

Purpose High-strength sutures allow tightening of a suture knot beyond the strength of the surgeon, possibly inflicting skin damage through the gloves. This study was undertaken to evaluate whether such effort is useful and how much tensioning on a surgical knot is necessary.

Methods Three different suture materials were tested: No. 2 Vicryl™, FibreWire™, and PDS™. First, the force spontaneously applied on sutures during experimental knot tightening ("tying load") was measured in fifteen experienced surgeons. Second, with each suture material, surgical square knots were tied with increasing, standardized loads (range 0.5–50 N) using a custom-made apparatus. Thereby, knot seating after tying was evaluated, and by loading the knots to failure, evaluation for failure mode and failure load was performed.

Results FibreWire™ 5-throw square knots always failed by complete slipping of all knots (resolving), independent on the tying load. A nonlinear decrease of knot slippage and increased failure load were seen with increasing tying loads for all sutures. Major differences were seen between 0.5 and 10 N for FibreWire™ (slippage: 25 mm) and PDS™ (99.6 mm), whereas Vicryl™ showed major differences (22.7 mm) between 0.5 and 2 N. Increasing the tying load from 10 to 50 N decreased the mean knot slippage from 12 (FibreWire™, ±2.6 SD), 9 (PDS™, ±1.8 SD) and 8 (Vicryl™, ±1.3 SD) mm to 6 (±2.9 SD), 3 (±1.5 SD) and 4 mm (±0.9 SD), respectively.

Conclusion Slippage and self-seating of the knots under load is unavoidable even with highest tying loads. Relatively minor but possibly important differences can be seen for tying loads exceeding 2 N (Vicryl™) and 10 N (PDS™ and FibreWire™) for failure load and knot slippage. But also with a tying load of 50 N, a minimal slippage of approximately 3 mm seems unavoidable for all suture types. However, it is important to state that intense tightening does not prevent knot resolution and is only necessary in clinical situations that demand very tight sutures. Numbers and proper appliance of throws are more relevant than tying strength to reach the maximum failure load.

Keywords Suture · Strength · Polyblend · Knot · Tying · Force

Introduction

Failure of surgical knots is known but often occult and most likely underestimated. Multiple studies and reports address optimal knot tying techniques for open and arthroscopic procedures, for all different types of braided or monofilament sutures [2, 3, 5–9]. It is common sense that a knot has to be tightened until it is snug, meaning to a load somewhat less than the failure strength of the suture; otherwise, the knot may fail.

With the advent of high-strength polyblend polyethylene sutures, knots can be tightened with loads that exceed a surgeon's physical strength and with the risk of self-inflicted skin lacerations through the surgical gloves. Even though many aspects for creating optimal sutures have

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S. Neuhofer (✉) · K. Wieser · D. Müller · C. Gerber · D. C. Meyer
Orthopaedic Department, Balgrist University Hospital, University of Zurich, Forchstrasse 340, 8008 Zurich, Switzerland
e-mail: dr.stefan.neuhofer@gmail.com

G. Lajtai
Orthopaedic Department, Private Hospital Maria Hilf, Klagenfurt, Carinthia, Austria

been investigated and published [1–9], data for the needed tying force could not be found. As we do not know whether such overzealous tightening is necessary or at least beneficial and what minimal force for tightening is needed, the following study has been undertaken to determine:

1. The actual force that is used by experienced surgeons for knot tying (tying load).
2. Force-controlled tying of knots with increasing steps according to the previously evaluated spontaneously applied forces on three different suture materials USP No. 2 PDS™, Vicryl™ and FibreWire™ and evaluation of whether the knots were seated snug.
3. Evaluation of knot failure load and failure mode by single load to failure testing.

It was hypothesized that there is an optimal tightening force for each suture type and that surgeons will tend to under- or overtighten sutures, as the ideal strength is not known yet.

Materials and methods

The setting was a controlled laboratory study.

In the first phase, the clinically used force for knot tying was evaluated. Based on this evaluation, knots were experimentally tied with standardized loads. Knot seating was documented at each load step. In the final phase, each tied knot was evaluated for knot slippage and maximum failure load (Newton—N) until rupture or resolving of the knot.

Evaluation of applied force on knots tied by experienced surgeons

USP No. 2 PDS™, Vicryl™ (Ethicon, Johnson & Johnson, Norderstedt, Germany) and FibreWire™ (Arthrex, Belp-Bern, Switzerland) threads have been tied on a custom-made apparatus (Fig. 1). We attached two threads to the apparatus, one at an immobile iron rod and one at the spring balance (0–100 N Range). Both sutures crossed in opposite directions through a small hole on the plate (Fig. 1—left arrow), representing the knot. While the surgeon pulled in opposite direction on the sutures, the maximally exerted force was measured on thread B, attached to the balance (see Fig. 1—right arrow). The test was blinded, as the spring balance was covered by a box and only the examiner had undisclosed insight. Accuracy: 1 N. 15 experienced surgeons participated in three simulated settings:

1. Open tied knots
2. Open tied knots using a needle clamp
3. Sliding knot tied as in arthroscopy using a knot pusher

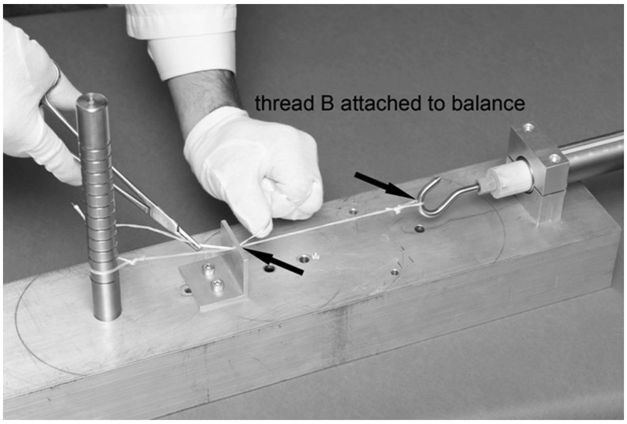

Fig. 1 Tying force evaluating custom made apparatus

Force-controlled knot tying

To test different knots, we decided to produce standardized suture loops with square knots, tied with varied loads and numbers of alternating throws. These loops were later to be tested mechanically.

Based on the evaluated data, we used the following forces for knot tying: 0.5, 1, 2, 5, 10, 20, 50 N. Again, a custom-made apparatus (Fig. 2) provided for controlled force application. An immobile iron rod served as attachment for the retention of one end of the suture. In the centre of the apparatus, a mobile cylinder (perimeter approximately 6 cm) was able to rotate freely around its longitudinal axis and to slide sideways. Knots were tied with the tested suture being wound around the cylinder, resulting in the standardized suture loop with knot. By alternating the upper or lower surface of the cylinder, an optimal alternating orientation of the throws could be achieved in a standardized fashion. On the free end of the suture, which was directed around a deflection pulley, a specific load (0.5–50 N) was attached and gently released to tighten the knot until the desired number of throws was reached. After completion of the knot, both ends were cut with a distance to the knot of 5 mm. For each thread type (No. 2 PDS™, Vicryl™ and FibreWire™), 7 samples per load step were tied. In total, 161 sutures, 5–7-throw square knots were tied and evaluated.

Knot seating

Knot seating was judged for each suture material for every load step. Three grades of seating quality were used: seated, partially seated and loose. “Seated” was defined as an optically perfectly snug knot without any visible gap between the square knots (e.g. see Fig. 3). “Partially seated” was defined as visible gaps between at least two square knots (e.g. see Fig. 4). “Loose” was defined as

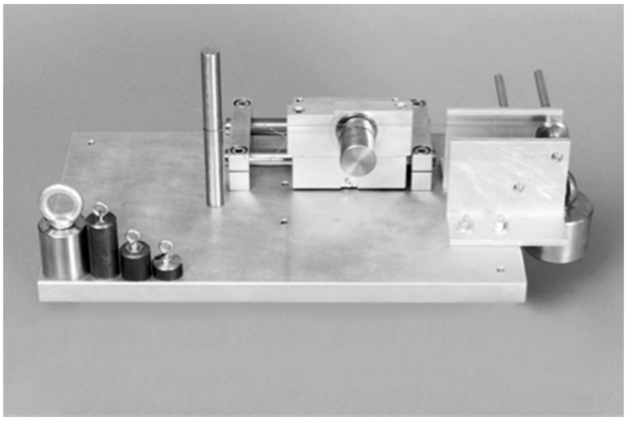

Fig. 2 Custom made apparatus for force-controlled knot tying

visible gaps between all square knots or spontaneous resolving of some square knots (e.g. see Fig. 5).

Single load to failure

To measure the slipping of the knot during testing, the threads were marked with a pen directly where they entered the knot. An universal materials testing machine (Zwick GmbH, Ulm, Germany) was used for single tensile loading until failure. The end points of the tensile tests were either rupture of the thread or complete resolving of the knot (failure load and failure mode). In case of rupture, further evaluation was performed by the measurement of knot slippage.

Statistical analysis

ANOVA analyses for variance and corrected post hoc tests were performed to determine significant differences. For the corrected post hoc tests, a p value of 0.05 was determined.

Fig. 3 Vicryl^{TM} #2 10 N

Fig. 4 Vicryl^{TM} #2 2 N

Fig. 5 Vicryl^{TM} #2 0.5 N

Results

Knot tying load of experienced surgeons

There was a vast variance of applied forces when tying a knot among the evaluated surgeons (Fig. 6), regardless of type of thread or knot tying technique. Overall, the range of applied force was 3–63 N among all surgeons, suture techniques and thread types. The mean applied force was 15 N (±9.8 standard deviation = SD) for open tied knots, 16 N (±9.7 SD) for knots tied with a needle clamp, and 17 N (±10.9 SD) for knots tied with a knot pusher.

Failure mode of knots tied with different loads and numbers of throws (Table 1)

Unexpectedly, all 5-throw square knots of No. 2 FibreWire^{TM} tied even with 50 N showed resolving after a mean single load of 222 N (±24.9 SD). FibreWire^{TM} 6-throw square knots tied with 50–10 N all slipped to a certain amount, then seated themselves and failed by rupture. There was one resolving of seven FibreWire^{TM} 6-throw square

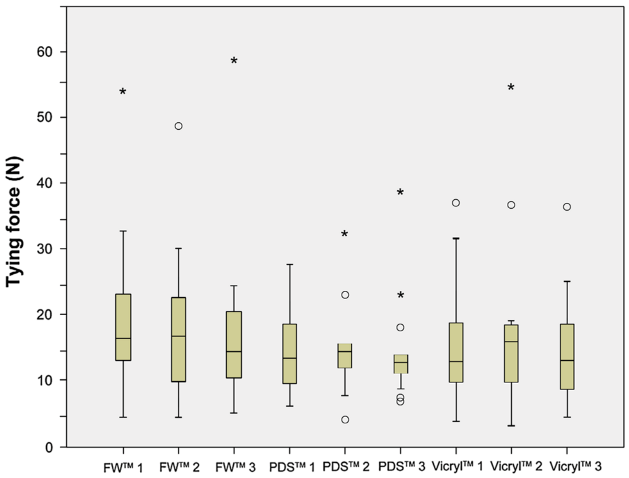

Fig. 6 *FW™1* FibreWire™, open tied using a needle clamp; *FW™2* FibreWire™, tied using a knot pusher; *FW™3* FibreWire™, tied by hand; *PDS™1* tied using a needle clamp; *PDS™2* tied using a knot pusher; *PDS™3* tied by hand; *Vicryl™1* tied using a needle clamp; *Vicryl™2* tied using a knot pusher; *Vicryl™3* tied by hand; (Accuracy 1 N)

knots tied with 5 N and four resolved knots of seven FibreWire™ 6-throw square knots tied with 2 N. Thus, 7-throw square knots were tied with 2–0.5 N, which showed one failure by resolving for each load step. There was no need to increase the number of square knots for Vicryl™ or PDS™. Failure by resolving of No. 2 Vicryl™ was seen in the following tying load categories: 0.5 N (1/7), 1 N (1/7), and 10 N (1/7). 5-throw square knots of No. 2 PDS™ showed failure by resolving in the following tying load categories: 2 N (2/7), 1 N (2/7), and 0.5 N (7/7).

Knots, failed by rupture, are evaluated in the following

Regarding load to failure, surprisingly small differences were seen between the differently tied knots (Fig. 7). However, FibreWire™ 6-throw square knots tied with 10 N showed significantly lower rupture load than tied with 50 N. For Vicryl™, tying the knot with 50 N was significantly better than lower loads. PDS™ did not show significant differences related to tying load. However, as seen above, many PDS™ failed by complete resolving, which, according to the testing protocol, caused a lower number of sutures per test to be statistically evaluated and a corresponding lack of significant results for PDS™. However, an obvious tendency for higher failure loads at higher tying loads is seen with a peak performance at 50 N tying load (see Fig. 7).

Knot slippage

Table 1 The number of knots failed by resolving

Tying load	FibreWire 5 throws	FibreWire 6 throws	FibreWire 7 throws	PDS 5 throws	Vicryl 5 throws
50 N	All	0	No results	0	0
20 N	No results	0	No results	0	0
10 N	No results	0	No results	0	1
5 N	No results	0	No results	0	0
2 N	No results	4	1	2	0
1 N	No results	No results	1	2	1
0.5 N	No results	No results	1	All	1 resolved

Continuous decrease of knot slippage was seen for higher tying loads. Major differences were seen between 0.5 and 10 N for FibreWire™ (24.8 mm) and PDS™ (99.6 mm), whereas Vicryl™ showed major differences (22.7 mm) between 0.5 and 2 N (see Fig. 8; Table 2). Multiple differences of knot slippage related to tying load were seen for all suture materials. Frequently though, there was no significant difference between increasing tying load steps, especially for high tying loads.

Knot seating regarding tying load

The optical appearance after tying the tested materials showed considerable differences. FibreWire™ appeared well seated at knot tying forces from 50 to 2 N. Only the categories 1 and 0.5 N showed partial seating and no knot appeared to be completely loose. Very different conditions were seen for PDS™, which was expected for a monofilament thread. Only 50 N tying load showed perfectly seated knots. Partial seating was seen for 20 and 10 N and everything below was considered as loose. The 0.5 N PDS™ even started to untie without manipulating. Vicryl™ showed seated knots from 50 to 5 N, partially seated knots at 2 N, and loose knots for 1 and 0.5 N.

Discussion

The most important finding of this study was that intense tightening of suture knots does indeed improve knot elongation under load. However, even excessive pulling on the knot does not prevent knot slippage if there is a too small number of square knots.

Intuitively, it appears that a knot should be tied until it is tightly seated; otherwise, it may fail. As demonstrated in our in-house survey, there is however astonishingly little to no consensus among surgeons how much pull on a suture is enough. In order to have maximal security, some surgeons even tie a knot until their fingers are injured despite the use of surgical gloves and there are companies marketing dedicated devices to protect the fingers. Particularly with the advent of the new high-strength polyblend polyethylene

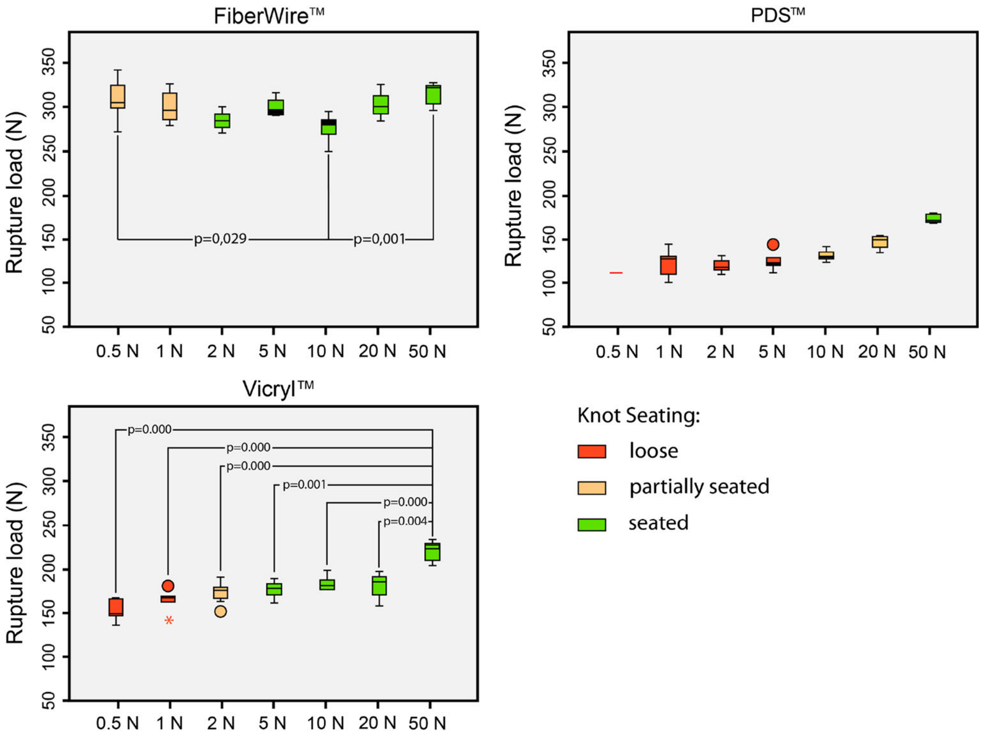

Fig. 7 Failure (rupture) load sorted by the applied tying loads (*x* axis); significant differences are displayed by *p* value. Whether knots were seated snug is sorted into three groups and *colour-marked*

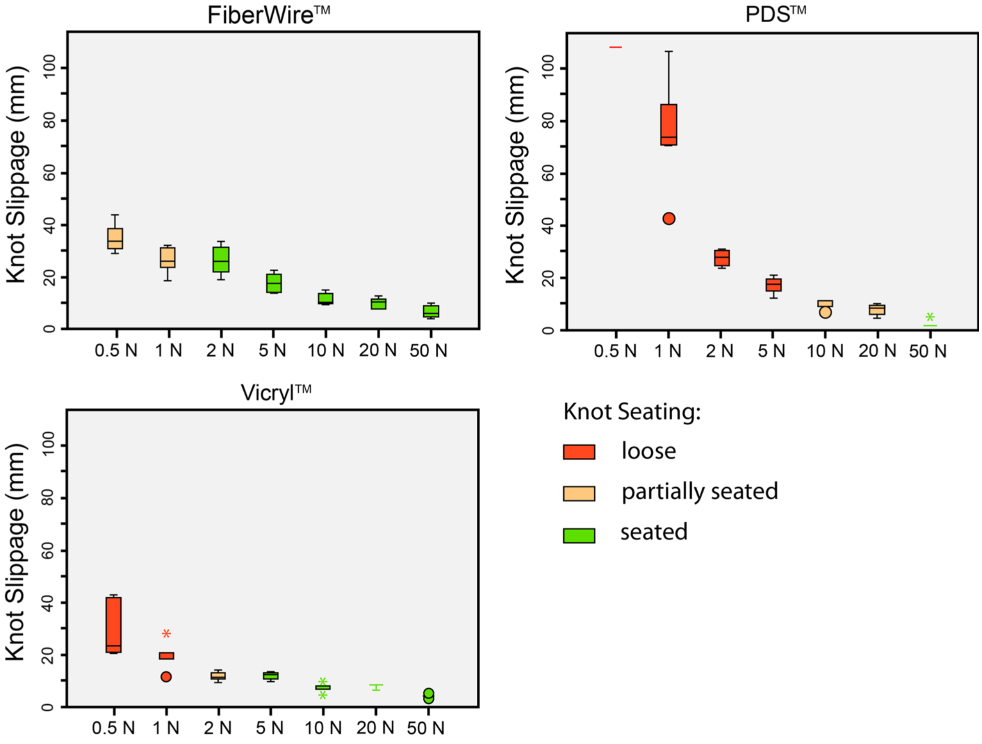

Fig. 8 Knot slippage related to used tying load (*x* axis) with colour-marked quality of knot seating

sutures, the importance of the knot has further increased and is clearly the weakest point in the suture construct. Therefore, we set out to define the influence of knot tying forces with varied numbers of throws on three types of sutures. It was found that very little loads are necessary to avoid knot resolution or to achieve maximal failure load, if an adequate number of throws are used, as the knots will self-tighten when under mechanical load. However, self-tightening is associated with considerable suture slippage within the knot, particularly of course if the knot is not fully seated. This slippage of the knot is most influenced by and can be reduced with the surgeons tightening effort, but

Table 2 Mean knot slippage for knot tying load from 50 to 10 N

	50 N	20 N	10 N
FibreWire	6 mm (±2.9 SD)	9 mm (±2.1 SD)	12 mm (±2.6 SD)
PDS	3 mm (±1.5 SD)	7 mm (±2.0 SD)	9 mm (±1.8 SD)
Vicryl	4 mm (±0.9 SD)	7 mm (±0.9 SD)	8 mm (±1.3 SD)

can even with overzealous pulling on the suture not be fully avoided. Even if the suture is tightened with maximal force (50 N), slippage occurs to a distance of at least 3 mm in FibreWire^{TM}, 2 mm in Vicryl^{TM} and 3 mm in PDS^{TM}. With the reduction in load from 50 to 10 N, the mean slippage distance will increase to 12 mm (FibreWire^{TM}), 8 mm (Vicryl^{TM}) and 9 mm (PDS^{TM}), however without reaching statistical significance.

Therefore, the hypothesis that there is an ideal tightening force for each suture cannot be confirmed, as increasing tying load further reduces the unavoidable knot slippage only little. Therefore, surgeons tend in general to over-tighten suture knots regarding the resolution of the knot, but the vast majority of the surgeons could improve knot slippage significantly and in a most likely unexpected amount with more vigorous pull. In PDS^{TM}, pulling until there are no visible gaps anymore between the suture loops may be regarded as a useful rule of thumb. The number of throws showed a clear impact on failure by complete resolving in low tying loads for FibreWire^{TM}. Thus, 7-throw square knots appear necessary for this suture.

Interestingly, failure strength increases if a knot is better seated, even if there is no resolution of the knot. We speculate that this may be explained with damage to the suture material during the self-tightening process in poorly seated knots. This is supported by the fact that this effect was particularly observed in PDS^{TM}, which may be more susceptible to structural damage due to its monofilamentous structure.

How much slippage is clinically acceptable depends on the specific situation. In previous studies, limits for failure of knots by slippage were set at relatively low values of 3 mm [2, 5, 7]; however, tying loads were not evaluated. In the present study, such low values were hardly ever achieved and seem not realistic for these suture types. This low value has already been questioned in a previous study, which also used this load for evaluation [6].

A limitation of this study is that it was restricted to the suture diameter of USP No 2, that is, 0.5 mm, single load testing, simple square knots and three types of sutures. However, as this size and class of sutures appear to be most popular for mechanically loaded surgical procedures, we considered this setting as properly representative to establish an adequate testing protocol. In further studies, other braiding configurations and material types, diameters and particularly knot types may be considered.

The testing of the number of throws confirmed previous reports that 5-throw square knots can be used as a gold standard for conventional suture materials, as failure most likely result by suture breaking, but for polyblend suture material more throws are necessary [9]. Particularly for FibreWire^{TM}, even very high tightening forces cannot compensate for an insufficient number of throws, with alternating square knots, there should be at least 6, preferably 7 throws [3].

Conclusion

Finally, the following conclusion can be made for the day-by-day clinical work:

As surgical knots will unavoidably seat themselves under load and therefore always some elongation at the knot will happen, it appears therefore reasonable to always tighten as hard as feasible and as the suture can bear. However, when tying FibreWire^{TM}, it is still necessary to use at least 6 or better 7 square knots or the knot will not hold under high load.

Conflict of interest The authors declare that they have no conflict of interest.

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