Heliyon 9 (2023) e19391

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Arthroscopic knots: Suture and knot characterisation of modern polyblend suture materials

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A R T I C L E I N F O

Keywords:
Arthroscopic knots characterisation
Knots
Tensile strength of knots
Contemporary UHMWPE suture
Suture and knot characterisation and orthopaedic surgery

A B S T R A C T

Objective: The primary aim of this study was to explore the relationship between the biophysical structure and function of modern suture materials. Particularly the suture's ability to withstand the stressors of surgery and how the material properties affect knot stability. The secondary aim was to investigate the effect that different knots have on the suture material itself. This study builds on previous research assessing suture and knot characteristics but in modern Ultra High Molecular Weight Polyethylene (UHMWPE) materials currently in widespread clinical use in arthroscopic surgery.
Methods: Three common UHMWPE sutures and one polyester suture were tested in both a dry and wet state using the Geelong, Nicky's, Surgeon's and Tautline knots. Tensile strength of knots was tested vertically at a 60 mm/min strain rate and 45 mm gauge length. Sutures were tied through a cannula around two 8 mm diameter circular bollards. Testing was conducted in a controlled environment temperature and humidity environment (20 ± 2 °C, 65 ± 2%).
Results: No one knot type was optimal over all suture types. Mean tensile strength in both a dry and wet state and a low coefficient of variation (CV) in tensile strength in a wet state were considered as an indication of suitability. With Ethibond sutures this was the Geelong knot (CV:4.2%). With Orthocord sutures both the Geelong and Tautline knots (CV:4.2% and CV:11.9% respectively). With FiberWire sutures the Nickys and Tautline knots (CV:22.6% and CV:22.5% respectively). With ForceFiber sutures all four knots exhibited similar wet tensile strength with high variability showing that all should perform in a similar way *invivo*.
Conclusions: This study demonstrates a statistically significant three-way interaction between polyblend suture materials, the knot and the environment. This has implications for knot security using the tested sutures in different environments, as one knot may not behave the same under all conditions.

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https://doi.org/10.1016/j.heliyon.2023.e19391
Received 16 December 2022; Received in revised form 2 June 2023; Accepted 21 August 2023
Available online 25 August 2023

1. Introduction

Arthroscopy has been one of the essential innovations in orthopaedic surgery in the past century [1]. Suture manipulation, less pain, and postoperative swelling with lower infection rates are some of the critical points which have made arthroscopy a preferred technique, with no exception for shoulder repairs [1,2,3]. The benefits of arthroscopy are exemplified by arthroscopic rotator cuff repairs, which have comparable results to open and mini-open techniques [4–6].

The increase in arthroscopic surgery is primarily due to instrument, technological and material advances not limited to but including suture anchors and contemporary suture material development [5–9]. It should be noted that suture material, its design, and mechanical properties have a proclivity not only to influence its behaviour clinically but also have different handling, and knot security properties [10–12]. The family of contemporary polyblend sutures has almost entirely replaced the previously conventional suture materials (Ethibond, PDS, Nylon, and Vicryl) in managing shoulder conditions. However, apart from their excellent resistance to tensile loads, evidence of in-depth analysis of suture and knot-tying characteristics of the modern ultra-high molecular weight polyethylene (UHMWPE) suture materials still needs to catch up in the literature.

Arthroscopy is inherently at risk, and repairs may fail at several sites during repair construction. The most common site of failure in rotator cuff surgery is the bone-tendon interface, but not necessarily in stabilisation surgery; however, the knot is the most modifiable site of failure within a repair. The knot is often an underestimated cause of repair failure and loss of tissue approximation [1,13]. Knot security is commonly determined by (1) biophysical properties of the suture, (2) knot configuration, (3) number of throws, (4) length of the suture loop, and (5) the moisture content amongst others [1,4,14,15].

The perfect arthroscopic knot should be reproducible and have high strength, low profile, and minimal slippage. For these reasons, the perceived gold standard of surgical knots is the Surgeon's knot for most procedures; however, it is not as secure as a sliding knot [4,7,8,16,17]. Hence the role of the suture and knot is integral in this construct. If the suture fails, the knot unravels, or if there is slippage of $>$3 mm then the tendon-bone apposition is lost, which negatively affects the healing process [1,8,9,18,19].

The modern braided, non-absorbable polyblend sutures materials were designed to be more durable and less fatigue-prone, allowing the tendon-bone interface time to heal and strengthen [18]. While a lot is known about the biophysical properties of first-generation suture materials such as Vicryl, Prolene, and to a lesser extent, Ethibond, there is only limited data on the modern braided, non-absorbable polyblend sutures [20,21]. Modern suture materials have been shown to have high tensile strengths and favourable handling qualities; however, there are concerns that the same coatings which make suture materials easier to handle may contribute to knot slippage and, as a consequence, clinical failure [9,10].

In this study, we aimed to compare modern polyblend suture and surgical knot combinations to traditional knot/material configurations. The null hypothesis proposed was that the contemporary polyblend suture materials have similar knot-tying characteristics to conventional polyethylene suture knot configurations.

2. Methodology

2.1. Materials

Four number two grade suture materials were compared: FiberWire™ (Arthrex, Naples, FL), Ethibond Excel™ (Ethicon, Somerville NJ), Orthocord™ (Johnson and Johnson De Puy-Mitek, Norwood, MA), and ForceFibre™ (Tornier, Stafford TX) [10] in combination with four commonly used knots; the Surgeon's Knot, Nicky's, Geelong (a modified Tautline hitch) and the Tautline, the latter three being sliding knots (Fig. 1).

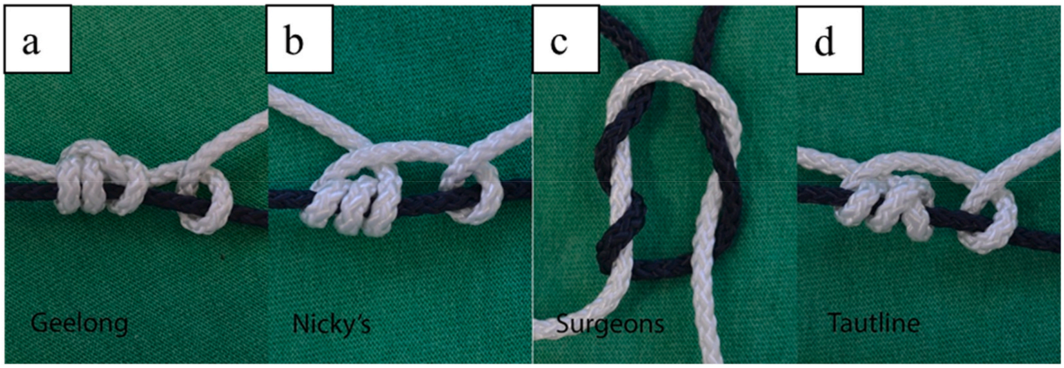

Fig. 1. Images of knots used tied with two coloured ropes for knot configuration clarity. These are the four commonly used knots: a) Geelong (a modified Tautline hitch), b) Nicky's, c) Surgeon's, and d) Tautline knot. Surgeon's knot is non sliding, and the rest are sliding knots.

2.2. Suture selection

FiberWire is a composite material that contains two components: a multi-strand UHMWPE core and a braided polyester and UHMWPE jacket. Orthocord™ has a polydioxanone (PDS) core (68%) with a UHMWPE sleeve (32%) and is coated in polyglactin. ForceFiber™ consists of a coreless braided material made from UHMWPE. Ethibond™ is made from a braided polyester coated with polybutylate [13]. The material properties of these have been reported on previously [10].

2.3. Knot tying

Senior medical students tied the knot with an Upper Limb Orthopaedic Fellow after training by the senior arthroscopic Surgeon. The knot tiers practiced the knots until they were proficient at tying them consistently, with minimum slippage variance under load. They were not blinded to the suture material they were using. All knots were tied with surgical instruments (knot pusher, cannula, and needle holders) to replicate the forces generated during arthroscopic knot tying. Knots compared were Nicky's, Geelong, Surgeon's, and Tautline. Each tied knot had three reverse half hitches on alternating posts to ensure the knot was secure [16,17,22]. Literature has shown that knots can have their security/strength improved with increased throws, but this comes at the cost of increasing the profile of the knot and, subsequently, the risk for foreign body reaction [7,9,3]. Previous research recommends the use of at least three reverse half hitches on alternating posts (RHAPs), as this has been shown to provide improved knot security on sliding knots [22,23–26].

2.4. Knot tying conditions

Each knot was tied sequentially with the same suture material with an alternating knots tier. Knots were tested in dry and wet conditions. The wet test was conducted after 24 h immersions of the suture materials in 0.9% standard saline solution (Baxter, Deerfield, IL). The suture and knot were tested for failure with the mode of failure recorded as either (A) Knot slippage (defined as the deviation of the load/extension curve from a linear trajectory) or (B) suture or knot breakage. Suture/knot failure was only recorded as a failure mechanism if knot slippage had not occurred first. One or more small knot slippages during the linear part of the load/extension curve were not considered to be the failure point of the knot/suture combination if the combined distance of slippage was less than 0.4 mm which was done in concordance with the previous literature [17,22].

2.5. Knot selection and mechanical testing

The Surgeon's knot is a typical open and arthroscopic knot with little internal security while tying but is also regarded as the gold standard for knot security once tied [27,28]. The Tautline knot was chosen as it has previously been shown to have superior knot security in conventional sutures [16]. In contrast, Nicky's knot is a modern developed knot that surgeons use commonly. Finally, the Geelong knot is a knot configuration that was developed to have the internal security of the Tautline knot but without its bulkiness and to have improved arthroscopic knot sliding characteristics.

Each length of suture material was cut to a minimum length of 250 mm using a suture cutter. Testing was conducted on a 5967 Materials Testing System (Instron Corporation, Norwood, MA, USA) with a 30 KN load cell, a 5 N preload, a 60 mm/min strain rate and a 45 mm gauge length.

Sutures were tested vertically and were tied through a cannula looped around two 8 mm diameter circular bollards to simulate arthroscopic knot-tying conditions. All testing was conducted in a controlled temperature and humidity environment (20 ± 2 °C, 65 ± 2%) at atmospheric pressure. The software used was BlueHill® 3 testing software (Instron Corporation, Norwood, MA, USA). A total of 7 samples were used for each knot/suture combination.

2.6. Statistical analysis

Statistical analysis was performed on a Statistical Package for the Social Sciences (SPSS, 25.01 Version, IBM Corporation, Armonk, NY). To demonstrate significant differences, the use of analysis of variance (ANOVA) method (one-way and multi-way), *t*-test (*p*-value), and post hoc (Tukey HSD) tests were conducted with a definition of significance ($p < 0.05$). All error bars shown are one standard deviation on either side of the mean.

3. Results

Most sutures (irrespective of knot type) had lower tensile strength in the wet state. Variations in wet and dry knot strength

Table 1
Mean of different suture strength in dry/wet condition.

Suture Condition	Ethibond	Orthocord	FiberWire	ForceFiber
Dry	125.5	125.9	190.8	166.4
Wet	96.7	102.3	169.7	186.2
Mean	111.1	114.1	176.3	180.2

suggested that each knot type needed to be investigated under each condition individually. Therefore, the mean suture strength (irrespective of knot type and environment) was not a good indicator of suture performance Table 1.

3.1. Ethibond suture materials

The Geelong knot performed well, both dry and wet (Fig. 2), with a low variation in tensile strength for the dry (CV:14.1%) and wet (CV:4.2%). The Tautline knot performed similarly to the Geelong knot in a dry state however, its reduced in wet strength suggests that it is less suitable for invivo use. The Tautline knot exhibited variation in tensile strength in the wet state (CV:11.9%).

Both the Nicky's and Surgeon's knot lost strength when wet with the surgeons knot also becoming highly unrepeatable (CV:64.2%). As most sutures are tied in a moist environment and spend their time *invivo* in a wet state, it would be best practice to avoid using both Nicky's and Surgeon's knots with Ethibond sutures.

3.2. Orthocord suture materials

The Geelong and Tautline knots had reasonably high variability in dry strength (CV:40.8% and CV:35.5%, respectively). However, both had low variation and good strength in the wet state (CV:4.2% and CV:11.9%, respectively) (Fig. 3). Both Nicky's and Surgeon's knot had a reduced wet strength. This result is similar to that seen with Ethibond, suggesting that they would be unsuitable for use with Orthocord.

3.3. FiberWire suture materials

While the Geelong knot had a reasonably dry mean tensile strength (Fig. 4) its reduction in wet strength and increased variability in a wet state (CV:33.0%) suggests that it would be unsuitable for use with FiberWire sutures. Nicky's knot performed well in both a dry and wet state but had a moderate variation in tensile strength (CV dry:20.1%, wet:22.6%). Like Nicky's knot, the Tautline knot performed well in tensile strength in the wet state and exhibited similar levels of variation (CV:18.1% dry and CV:22.5% wet) to Nicky's knot. Finally, the Surgeon's knot had significantly reduced wet strength, suggesting it would be unsuitable for use with FiberWire.

3.4. ForceFiber suture materials

All four knots exhibited similar wet tensile strength (Fig. 5), showing that all should perform in a similar way *invivo*. The Geelong knot had lower dry tensile strength, differing from other sutures. Almost all knot types exhibited moderate to high levels of dry and wet variability in tensile strength when tied with ForceFiber.

An independent sample *t*-test was conducted using IBM SPSS software (2-tailed, equal variances p-value) to address whether the tensile performance of each suture was significantly different in two conditions (dry/wet). The results are presented in Table 2. Nicky's and Surgeon's knots tied with Ethibond or Orthocord sutures displayed a significant difference in tensile performance ($p < 0.05$). For FiberWire suture, the tensile performance of the Geelong and Surgeon's knots showed a significant difference. Only the Tautline knot with ForceFiber suture demonstrated a significant difference between dry and wet conditions.

The significant difference between knots in each suture and condition was analyzed via a post hoc test (Tukey HSD, one-way ANOVA). Table 3 showed a significant difference between three-knot groups: Geelong-Nicky's, Geelong-Surgeon's, and Surgeon's-Tautline with Ethibond suture in wet conditions. The Orthocord suture showed similar results to that seen with Ethibond when wet. Different knots with FiberWire suture had significant differences in dry and wet states. The tensile performance of the Tautline knot with ForceFiber displayed significant differences with the other three knots when it was dry. However, the significant difference

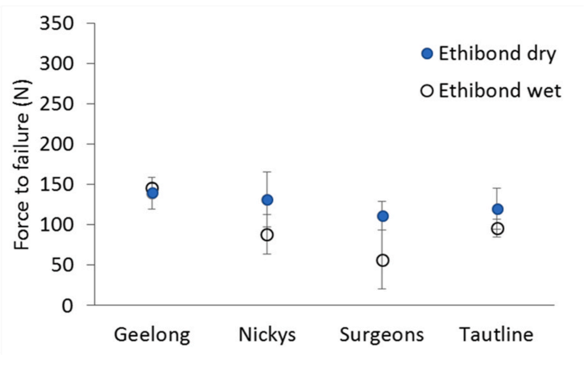

Fig. 2. Tensile performance of all knots on Ethibond sutures in both a wet and dry state. Geelong knot performed well in both dry and wet state, Tautline knot performed similar to Geelong knot in dry state whereas in wet state it lost its tensile strength which was similar to that of Nicky's and Surgeon's knot.

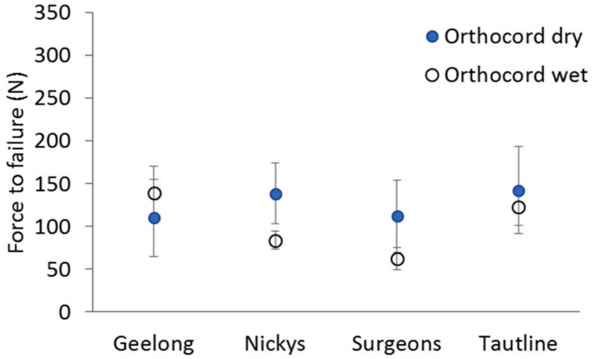

Fig. 3. Tensile performance of all knots on Orthocord sutures in both a wet and dry state. Geelong and Tautline knot exhibited reasonable wet strength whereas that of Nicky's and Surgeon's knot was low.

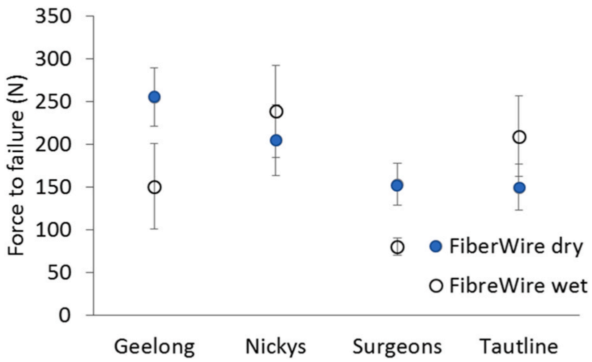

Fig. 4. Tensile performance of all knots on FiberWire sutures in both a wet and dry state. Tensile performance of all knots on FiberWire sutures in both a wet and dry state. Geelong knot performed reasonably well in dry state. Nicky's knot performed well in both dry and wet state which was similar to Tautline knot whereas the Surgeon's knot had significantly reduced wet strength.

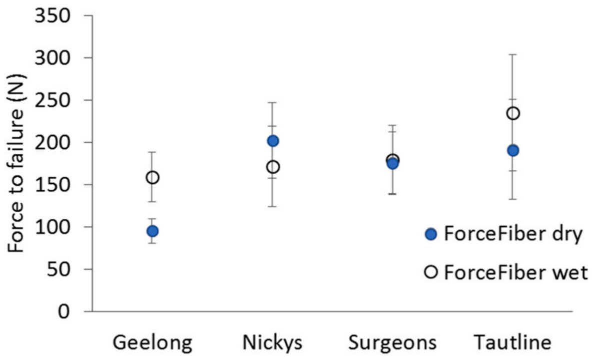

Fig. 5. Tensile performance of all knots on Force fibre sutures in both a wet and dry state. All four knots exhibited similar wet tensile strength. The Geelong knot had lower dry tensile strength, differing from other sutures.

Table 2
t-test results of tensile performance in dry and wet conditions (*p*-value, 2-tailed).

Knot Suture	Geelong	Nicky's	Surgeon's	Tautline
Ethibond	0.471	0.026*	0.004*	0.056
Orthocord	0.213	0.004*	0.018*	0.403
FiberWire	0.005*	0.249	0.000*	0.020
ForceFiber	0.250	0.848	0.368	0.000*

Note: *: Significance ($p < 0.05$).

Table 3
Post hoc significance values for tensile performance (one-way ANOVA).

Knot	1	2	3	1	2	3
	Ethibond dry			Ethibond wet		
K1						
K2	0.945			0.001		
K3	0.200	0.468		0.000	0.109	
K4	0.531	0.846	0.921	0.005	0.936	0.032
	Orthocord dry			Orthocord wet		
K1						
K2	0.675			0.001		
K3	1.000	0.722		0.000	0.292	
K4	0.582	0.999	0.629	0.530	0.016	0.000
	FiberWire dry			FiberWire wet		
K1						
K2	0.060			0.039		
K3	0.000	0.051		0.018	0.000	
K4	0.000	0.034	0.998	0.326	0.699	0.000
	ForceFiber dry			ForceFiber wet		
K1						
K2	0.917			0.959		
K3	0.969	0.696		0.840	0.987	
K4	0.003	0.014	0.001	0.034	0.092	0.167

Note: The mean difference is significant under the 0.05 level (<0.05), K1: Geelong, K2: Nickys, K3: Surgeons, and K4: Tautline.

reduced dramatically in the wet state.

An ANOVA multiple comparisons was performed to determine the multi-factor interaction influence. Table 4 presents a significant difference in variables. Each variable (suture, knot, and condition) and the interactions between variables significantly impacted tensile performance. In contrast, the interaction of variables had an insignificant influence on the extension performance.

3.5. *Mode of failure*

Failure of the knot/suture combination was taken at the point of deviation from a linear path of the load/extension curve. Two predominant failure types were observed: suture/knot breakage and knot slippage. Suture or knot breakage predominately gave a linear load/extension curve followed by a rapid load drop indicating the breakage point (Fig. 6 ①). Knot slippage conforms to three

Table 4
Tests of between-subjects effects (ANOVA multiple comparisons).

Source	Sum of Squares	Degree of freedom	Mean Square	F value	Significance *p*
Tensile					
Corrected Model	560383.299[a]	31	18076.881	12.045	**0.000**
Intercept	4776038.741	1	4776038.741	3179.650	**0.000**
Suture	249764.953	3	83254.984	55.427	**0.000**
Knot	66754.748	3	22251.583	14.814	**0.000**
Dry/Wet	8965.433	1	8965.433	5.969	**0.015**
Suture × Knot	121205.065	9	13467.229	8.966	**0.000**
Suture × Dry/Wet	20227.402	3	6742.467	4.489	**0.005**
Knot × Dry/Wet	28674.013	3	9558.004	6.363	**0.000**
Suture × Knot × Dry/wet	74414.301	9	8268.256	5.505	**0.000**
Error	289898.401	193	1502.064		
Total	5604359.867	225			
Corrected Total	850281.700	224			
Extension					
Corrected Model	14351.747[b]	31	462.960	3.047	**0.000**
Intercept	68961.509	1	68961.509	453.852	**0.000**
Suture	4268.462	3	1422.821	9.364	**0.000**
Knot	3786.167	3	1262.056	8.306	**0.000**
Dry/Wet	1306.783	1	1306.783	8.600	**0.004**
Suture × Knot	1429.563	9	158.840	1.045	0.405
Suture × Dry/Wet	955.462	3	318.487	2.096	0.102
Knot × Dry/Wet	635.883	3	211.961	1.395	0.246
Suture × Knot × Dry/wet	2011.539	9	223.504	1.471	0.161
Error	29477.755	194	151.947		
Total	112534.760	226			
Corrected Total	43829.502	225			

[a] R squared = 0.659 (adjusted R squared = 0.604).
[b] R squared = 0.327 (adjusted R squared = 0.220), and Significance ($p < 0.05$).

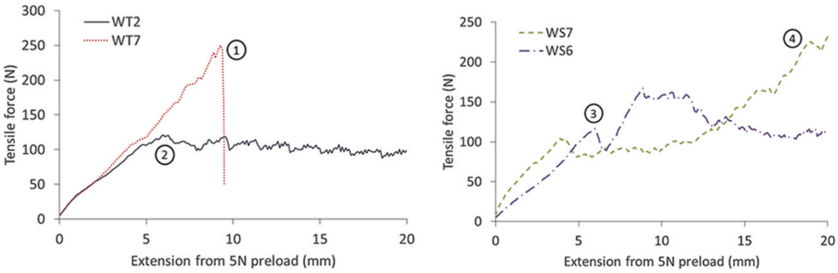

Fig. 6. Load/extension curves for the most common knot/suture failure types. Samples displayed are wet (W) ForceFiber sutures tied with either a Tautline (T) or Surgeon's knot (S). (1) point of knot/suture breakage. (2) point of knot slippage. (3) point of knot configuration readjustment. (4) point of increased load after extensive knot slippage.

main load/extension curve shapes. In many cases, the load increased to the point where knot slippage occurred, causing the load to gradually fall off in a hacksaw tooth fashion (Fig. 6 ②). The knot sometimes underwent a minor point slippage or configuration readjustment (Fig. 6 ③) before recording a higher peak load. This peak load can be followed either by a knot/suture breakage or prolonged knot slippage (as shown in the plotted result). The point of maximum force was taken at the first peak on the linear portion of the load/extension curve of this type of failure unless the duration of the load drop was less than 0.4 mm, and then it was taken as the end of the linear portion of the plot. In several cases, after a significant period of knot slippage, the knot reconfigured and caused a load higher than the initial load achieved before knot slippage. In this case, the point of deviation from the linear of the first peak load was taken as the point of failure as the peak load was often after significant knot slippage (Fig. 6 ④).

There was a high rate of knot slippage (80%) amongst all suture types. Orthocord and ForceFibre had high rates of knot slippage (100%) compared to Ethibond and FiberWire (51% and 69%, respectively). For Ethibond and ForceFiber, slippage was more likely to occur with a wet knot versus a dry knot (Table 5). However, knot slippage should not be viewed as a negative point, as it often occurs when there is a moderate to high load.

4. Discussion

This study suggests that with knot tensile strength, there is a statistically significant three-way interaction between the suture material, the knot, and the environment. It also further outlines the significant difference between the performance of modern polyblend suture and knot combinations when compared with the more traditional suture material combinations. This is important to consider as arthroscopic procedures rely heavily on the mechanical stability of the suture knot construct and have been proven to influence the bone-suture-tissue interface and knot security to affect biological stability for repair and healing. As mentioned, this system's knot security is the component most influenced by the materials used and the surgeon's use [20]. This is why knot type and the suture material chosen are paramount to both initial healing (due to tissue approximation) and the longevity of a successful arthroscopic repair [26]. This research further highlights that little is known about modern common-use materials and the interplay with knot security under differing conditions.

Utilising Ethibond as the comparator was necessary for this study to investigate the integrity of knot tying with contemporary UHMWPE suture material as it has been widely studied and has accessible experimental data on knot tying characteristics, knot strength, and tensile strength. The modern UHMWPE suture materials chosen for this study were consistent with previously chosen materials for tensile strength testing and represented commonly used contemporary sutures on the market. Fiberwire has been shown to have the most significant resistance to abrasion and tensile load. At the same time, Orthocord is preferred for its absorbable PDS core that allows the material to flatten with time in vivo and have a less bulky knot configuration. Finally, ForceFiber was chosen as it is typical of the remaining UHMWPE suture materials.

For a suture and knot to undertake its function, it must meet several important parameters. For example, it should be easily tied and moved into place within the body; it should be easily repeatable, providing uniform knot strength, it should have a tensile strength that is high enough to perform the task assigned to it, and it should not have a significant increase in length when a small tensile load is applied to it. In this study, each of these factors was investigated. The repeatability of the tensile properties of the knot is important. The knot tensile strength coefficient of variation (CV) of a knot indicates knot repeatability. A low CV would suggest that a knot may be tied repeatedly with confidence in its integrity. Although a knot is often tied using a dry suture, structural integrity in a wet state is just as important as loading will occur on the suture during limb movement post-surgery when the suture has absorbed fluids from the body to wet its structure.

Previous studies have shown that sliding knots are more potent than square knots [22]. This work showed that the knot depends on suture type, and neither square nor sliding knots should be compared as superior. It is only after a study of the strength of the knot with the suture to be used has been conducted that a true understanding can be established. This work employed four knots, and all four performed differently on each suture material. Each knot type employed was suitable for use with one of the four sutures investigated. The exact factors for the suitability of knot type were not established; however, suture parameters such as coating type, presence of a core, sheath fibre type, and filament parameters could be assumed to be an influencing factor. In the future, it would be beneficial if sutures were supplied with recommended knots to avoid using inferior knots.

Table 5
Mode of failure.

Suture Mode	Ethibond dry/wet	Orthocord dry/wet	FiberWire dry/wet	ForceFiber dry/wet
Suture/Knot	20/8	0/0	0/0	12/6
Slippage	9/20	28/28	28/29	18/22

Slippage was a significant failure mode (89.5%) with contemporary UHMWPE suture materials. The observed high rate of slippage associated with UHMWPE sutures has been previously attributed to smoother surfaces and, therefore, lower friction coefficient when compared to polyester equivalents [7,18]. This work found that there may still need to be more to guarantee knot security in modern suture materials and therefore utilise their potential tensile strength. It has been previously published that at least three reverse half-hitches on alternating posts (RHAPs) are necessary to provide knot security on sliding knots; this was adopted in the methodology of this study [17,3,23,24]. This work found that there may still need to be more to guarantee knot security in modern suture materials and therefore utilise their potential tensile strength. The high rate of knot slippage resulted in the ultimate tensile strength of the suture needing to be achieved with the suture/knot composite. Barber et al. postulated a similar theory and felt that more throws might be required to improve security [14]. This, however, comes at the cost of increasing the profile of the knot and, subsequently, the risk for foreign body reaction or abrasion, further research is required to assess this [7,16,22].

As defined in this study, slippage should not be considered a negative point. Fiberwire tied with Nicky's knot was an excellent example of this statement, with a mean dry strength of 204.9 N (CV: 20.1%) and a mean wet strength of 238.4 N (CV: 22.6%). All 14 test samples failed due to knot slippage; however, a high mean tensile strength was recorded in the suture before slippage occurred. Most knots will fail due to slippage or from tensile damage to the suture caused by the knot geometry. A knot that achieves an acceptable tensile load before slipping may be considered to have done its job successfully, with the loads likely to be encountered post-operative. Not studied in this work was the effect that cyclic loading may have on knot slippage. A knot that achieves an acceptable tensile load in a single test may still be unsuitable due to slippage induced by cyclic loading.

One of the most significant findings in this study was the relatively low load to failure of all the suture types studied and the level of variation seen from one knot/suture combination to another. Considering the importance of knot security in arthroscopic surgery, this reminds us that our surgical knots are not as secure as we assume, especially when placed under tension, such as static post-surgical muscle tensile loads. Furthermore, it reinforces concerns that arthroscopic knots may not be as secure as hand-tied knots. However, this can only be confirmed with research comparing the two modalities of knot tying.

Limitations to the study included a laboratory setup where the surgical environment could not be replicated. While we attempt to imitate surgical conditions by using knot pushers and physiological solutions, we acknowledge that the conditions differ from those encountered clinically. We are unable to replicate this with the use of the mandrel knot tying onto biological tissue. Further limitations of the study involve the decision to only use three reverse half-hitches on alternating posts to secure the initial loop and prevent loosening [22,27]. While there is evidence to support three RHAP provides sufficient knot security in conventional sutures [14], this may not be sufficient when using UHMWPE and hence warrants further investigation to determine the optimum number to achieve this. As previously mentioned by Barber et al., [14] these studies "do not determine how strong a suture needs to be in order to be 'strong enough''. That is, there is a minimum tensile strength that the suture material and knot combination must withstand in order to maintain tendon-bone apposition and hence adequate healing. Translating laboratory observations into clinical relevance without knowing these parameters is challenging.

A further limitation of this work was the assessment of pre-wet sutures. Usually, under clinical conditions, a suture material is dry when it is inserted into the body, with subsequent wetting of the suture and knot occurring in *vivo*. These conditions are hard to replicate, so an already wet suture was used for this study. The pre-wet suture may provide different sliding and knot characteristics to a knot that is tied dry and undergoes subsequent wetting in *vivo*.

Further limitations around our methodology were associated with loading to failure. As discussed by Najibi et al. cyclic loading may have been appropriate as it would allow for the investigation of knot creep [29] and warrants investigation. However, we endeavoured to investigate static load conditions in our study.

Finally, the arthroscopic knots were conducted by medical students with minimal experience in tying arthroscopic knots. While they did have extensive practice under supervision by the senior author, accounting for the learning curve to tie these knots consistently needed to be factored in, neither was the lack of blinding to the suture material being tested.

5. Conclusion

Our research showed that the null hypothesis was disproved, and there is a biomechanically significant difference between knot characteristics of contemporary polyblend suture materials versus conventional polyethylene suture materials such as Ethibond, which is likely to be clinically significant. More importantly, it showed that no uniform suture/knot combination outperformed the other suture/knot combinations, indicating that the new UHMWPE suture materials may need to utilise their increased tensile strength fully. Therefore, surgeons need to familiarise themselves with the materials they are using and the knots they are trying to take advantage of these fully proposed improved biomechanical properties and potentially consider different knot/suture combinations for different surgical circumstances.

As UHMWPE materials are the most commonly used suture materials for arthroscopic surgery, further evaluation of their performance from a biophysical surgeon handling and functional point of view is required [1,17].

Declarations

Author contribution statement

Earle Savage: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Christopher J. Hurren: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Gayathri Devi Rajmohan, Ph.D.: Analyzed and interpreted the data; Wrote the paper.

William Thomas: Performed the experiments; Analyzed and interpreted the data.

Richard S. Page: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supp. Material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge DePuy Synthes and Mitek for providing the anchors and sutures used for testing.

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