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REGULAR ARTICLE

Influence of Tubular Braid's Structures on Wicking Behaviours: An Experimental Investigation

Ghazal Ghamkhar[1,2] · **Mehrdad Arianpour**[1] · **Mahdi Bodaghi**[2]

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Abstract

Avoiding wicking in a suture to recover the wound and avoid infection is critical. In this paper, the capillary rise method is applied to evaluate the wicking property of tubular braided structures. Effects of the tubular braid's structural parameters, namely braid angle, interlacement pattern, structural axis, and the position of the yarns parallel to the axis are investigated. The results indicate that with the increase in braid angle, the wicking height descends and has the greatest effect on the wicking property among the studied parameters. It is also observed that under the same braid angle, the wicking height of the Two over Two braid is larger than the regular braid. Moreover, the presence of core yarns in a braided structure increases the wicking height. Among the studied parameters, the structural axis does not have a significant effect on this behavior. The results of statistical study confirm the experimental data and show that it is better to use biaxial braided structures with a regular pattern in the production of braided sutures. This work not only examines some factors effect on a vital feature of the braided suture but also underlines the importance of choosing the braid suture.

Keywords Tubular Braid · Wicking · Structural Parameters · Capillary Action · Experimentation

1 Introduction

The gadgets or tissues positioned inside or on the body's surface to replace missing body parts, the drug delivery, monitor body functions, or provide aid to organs and tissues are known as medical implants [1]. One of the most critical medical implants is sutures. A suture produces by fibers or multifilament yarns in two groups absorbable or non-absorbable sutures depending on tissue responses and the final feature expected from the sutures in losing tensile strength after a certain period or remaining unchanged with the biological activities of body tissues. It is necessary to mention that if multifilament yarns are used in production, the product is called braided sutures [2–8].

A Suture plays an important role in wound repair such as closure of skin wounds. So, it uses for different surgery applications such as the musculoskeletal system, vascular surgery, ocular surgery, plastic surgery, and neurosurgery. Different parameters determine the kind of suture material: physical and biological properties of the material which is used in production of a suture, assessment of the wound, and the healing rate of different tissues. Therefore, physical properties of a suture, handling characteristics, and biological properties characterized the performance of the suture. Although other parameters also involved such as good handling characteristics, good knot security and tensile strength, easy to sterilize without alterations to its properties, being nonelectrolytic, nonferromagnetic, noncapillary, nonallergenic, and noncarcinogenic, and provide a medium for bacterial non-growth, also being resistant to shrinkage and absorbed with minimal tissue reaction and be economical to use leading to make an ideal suture [9]. Suture classification is done based on absorbability (absorbable and non-absorbable), size (USP and EP. USP is used most commonly, and the size represents by a series combination a zero and any number other than zero, while EP represents the code ranges from 0.1 to 10), and physical configuration of the threads producing the suture (monofilament, multifilament, twisted, and braided) [10].

✉ Mahdi Bodaghi
mahdi.bodaghi@ntu.ac.uk

[1] Textile Engineering Department, Amirkabir University of Technology, Tehran, Iran

[2] Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, UK

The production steps of a biodegradable braided suture to end users are shown in Fig. 1. As can be seen, a biodegradable braided suture manufactured by the braiding method should be attached to a needle first. Then, the needle-attached suture is sterilized by Ethylene Oxide (E.O) or gamma. This product is put into a box and used by the surgeon on the patient who needs it.

A suture provides an optimal wound-healing setting, it is an important surgical aid to wound closure. In addition, they should prevent the penetration of fluids into the body, especially in infectious and inflammatory conditions. This is known as the wicking effect and is determined in different ways by measuring the amount of liquid penetration [8]. In general, wicking takes place when a liquid move along the surface of the fiber but is not absorbed into the fiber [11]. The wetting and wicking behavior of the fibrous structures has long been the matter of concern of both academia and industry because of the key role it plays in many applications, including apparel and non-apparel end uses, and manufacturing processes such as dyeing, finishing, and coating [12]. Wetting is a complex process complicated further by structure of the fibrous materials e.g., yarns, braid/woven/nonwoven/knitted fabrics, and pre-forms for composites. Wicking in fibrous materials is a very complicated, multi-aspect phenomena [13]. This marvel phenomenon plays a critical part in some potential applications of nanofiber yarns such as drug loaded sutures, humidity sensors. Papers showed that not only the liquid wicking height in the yarn is independent of fiber quantity in the cross section and increasing the quantity of the fibers will increase the uptake of water but also the wicking at the beginning of the capillary rise, the height of wicking follows Lucas–Washburn law [14].

In dealing with fibrous materials like braids, the wicking property would be a result of the synergistic wicking behavior of both constituent yarns and the corresponding structure. Moisture flow through braided structures is important in various range of its applications, including candle wicks, heat pipes, surgical sutures and preforms for composite materials [15–17]. Therefore, in many cases, the behaviors of different composites have been investigated in a dry state and not in a state where moisture has penetrated them [18, 19]. One product of the practical applications of the capillarity phenomena is the heat pipe. Usually, a heat pipe contains porous structures as capillary paths for working fluids inside the tube to make a complete circulation of two-phase flows without external pumping [15].

In braided composites, the performance of the composites is governed by the adhesion between the constituent fibers and resin binders. The adhesion between the fibers and resin is influenced by the initial wetting of the fibers by the resin as this decides the subsequent resin wicking between the fibers and voids content. In other words, permeability is a critical parameter to resin transfer process and produce a composite. On the other hand, surgical braided sutures should not let liquid pass through easily [13, 20]. Recently, efforts have been made to measure the wicking properties, capillary rise, and water transport in textiles [21–23].

Despite the importance of wicking property of braids, it has been overlooked in researches. There are several methods to investigate wicking properties. Fundamentally, liquid absorption in textile structures is typically studied in one of two ways; by measuring the height of liquid front or by measuring the weight of liquid absorbed as a function of time. Both techniques are useful, and they have their own special significance. For example, in applications such as coating, spraying, and resin impregnation of composite

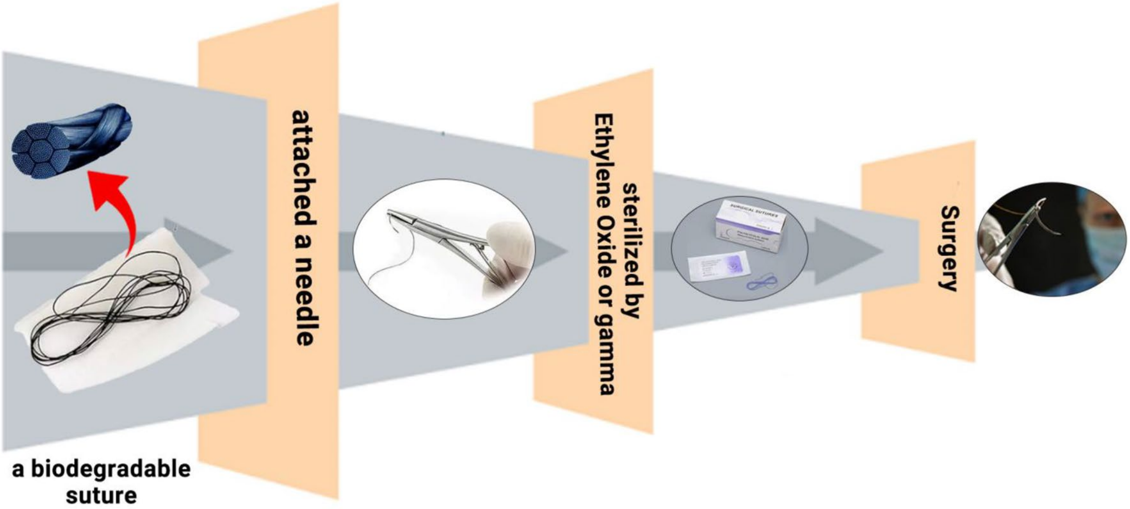


Fig. 1 Production steps of a biodegradable braided suture to end user

materials, measurement of the height of liquid front is more relevant than measurement of the weight of the resin. However, in many other applications in which knowledge of the amount of liquid absorbed is more crucial, gravimetric method is an appropriate method [24].

Since the material properties of a suture determine post-surgical wound healing, understanding the properties of suture materials is essential. One of the critical properties is to prevent the penetration of fluids that inversely relates to wicking behaviors. The aim of this paper is to achieve a suitable structure for the production of suture and to evaluate the effect of the tubular braid's structural parameters, such as interlacement pattern, braiding angle, structural axis (biaxial and triaxial), and the position of the yarns parallel to the axis (axial or core) on the wicking behaviors by using the video-metric method. To do this, twelve different tubular braided structures were produced by twistless multifilament polyester yarn on a 24-carrier Maypole braiding machine with 12 axial yarn feeders. The wicking property was measured by the video-metric method. Since the study aims to check the speed of liquid penetration, it focuses to minimize moisture absorption in the fiber. Therefore, it can be claimed that the novelty of the current research is not only in examining one of the most complex and critical suture parameters but also in helping to choose the appropriate structural parameters of a braided suture.

2 Materials and Method

2.1 Fabrication of Braid Structures

To achieve the purpose of this study and investigate the effect of the tubular braid's structure on the wicking behavior, twistless multifilament polyester yarn with a count of 1500 denier consisting of 460 filaments was used to produce the samples. The reason for choosing this fiber is its moisture absorption. Two-dimensional biaxial and triaxial tubular braid structures were produced according to Table 1 on a Maypole braiding machine, equipped with 24 braider yarn carriers and 12 axial yarn feeders.

Figure 2 shows a schematic of the constituent yarns in a braided structure and the braiding angle (θ). It is necessary to mention that the interlacement of the braiding yarns is known as a weaving or interlacement pattern. Also, the axial yarn is known as middle-end-yarn.

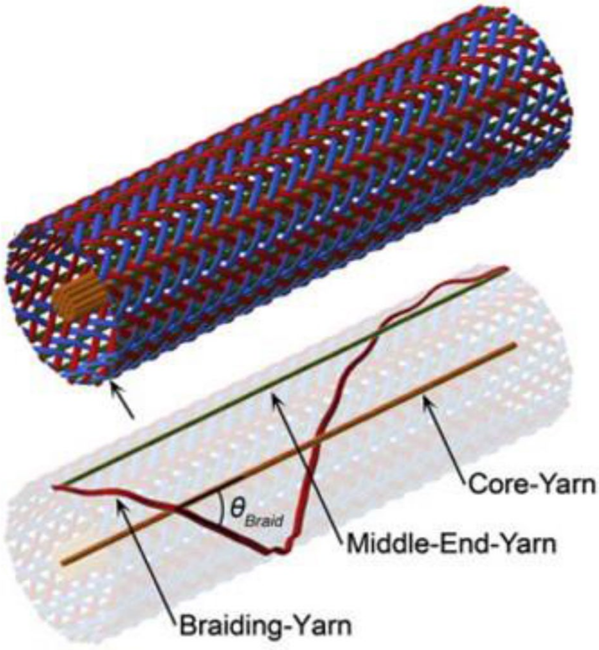


Fig. 2 Schematic of the constituent yarns in a braided structure [25]

Table 1 Specifications of tubular braids

Sample code	Braid angle (°)	Interlacement pattern	Core	Structural axis	Pick count (dm^{-1})	Linear density (tex)
20-R-B	20	Regular	Hollow	Biaxial	39	4467
30-R-B	30	Regular	Hollow	Biaxial	80	5000
30-T-B	30	Two over two	Hollow	Biaxial	39	5033
20-T-B	20	Two over two	Hollow	Biaxial	20	4500
30-T-A	30	Two over two	Hollow	Triaxial	39	8333
20-T-A	20	Two over two	Hollow	Triaxial	19	4433
30-R-A	30	Regular	Hollow	Triaxial	77	7800
20-R-A	20	Regular	Hollow	Triaxial	37	6567
20-T-C	20	Two over two	Yarn-cored	Biaxial	19	6433
30-T-C	30	Two over two	Yarn-cored	Biaxial	39	7033
30-R–C	30	Regular	Yarn-cored	Biaxial	75	7167
20-R–C	20	Regular	Yarn-cored	Biaxial	36	6600

Samples with different braid angles were produced by changing the process parameters of the braiding machine, i.e., the ratio of angular speed of carriers to take-up speed of the machine. To study the effect of braids' weave pattern on the wicking behavior, two different types of yarn interlacement, including 2/2 (Two over Two) and 1/2 (regular), were selected. Each weave pattern was created by changing the order of yarn carriers on the braiding machine. Figure 3 shows the schematic of the different sample's parameters.

2.2 Pre-treatment of Samples

Before measuring the wicking property of the braid samples, it is necessary to wash them in boiling water to remove the material added to the polyester yarns before braiding, such as spin finishing oils. After the washing process, samples were dried and kept at 25 ± 2°C temperature and 50 ± 5% relative humidity for 72 h.

2.3 Test Method for Measuring the Wicking Property

The test for determining the wicking height of liquid or the wicking property of the braid samples had performed to investigate the effect of the braid structure on this property. This test was conducted using a device whose schematic is shown in Fig. 4.

In this device, the sample placed vertically. So that the lower end placed in a small amount of a mixture of distilled water and blue ink. It is necessary to mention that the addition of ink gives a better view of liquid wicking, and its effect on the wicking property was insignificant. This method is also known as the Byreck method.

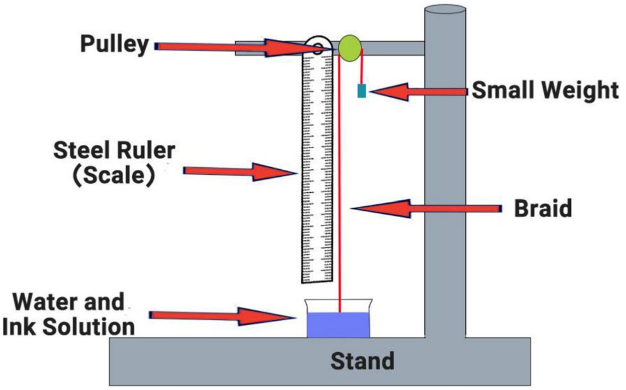


Fig. 4 Schematic of the device used to test liquid wicking

The height of the absorbed water in the samples is equal to the altitude of the adsorbed blue dye. The height of the absorbed water, which is marked with blue, was measured at certain times during 30 min.

This test was performed for each sample at different intervals for 30 min at 1 min intervals. Each sample was tested in 5 replications, and the mean height of liquid capillary wicking in 5 measurements was introduced as the

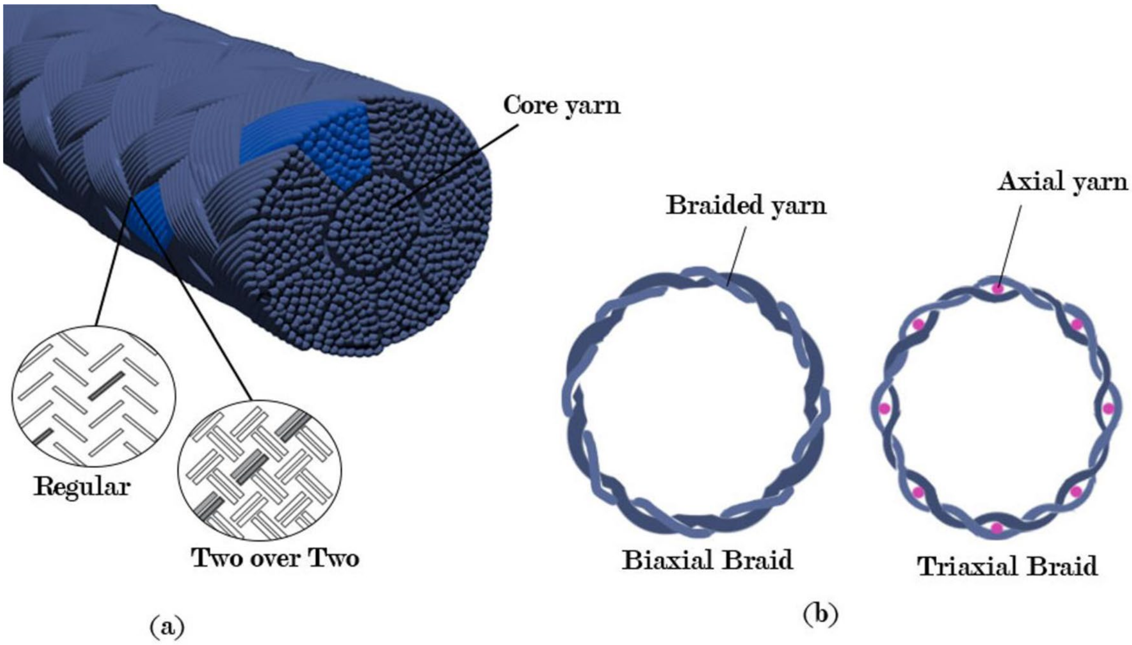


Fig. 3 Schematic of the different sample's parameters: **a** different weaving pattern in a yarn-cored biaxial braid, **b** different cross section of the biaxial and triaxial braid

final value of liquid wicking for a sample. A total of 60 samples were tested.

3 Results and Discussion

To investigate the effect of different braid's parameters on the wicking behavior, samples were divided into different comparable groups. The classification of the samples and the parameters to be compared in each group are given in Table 2.

3.1 Investigating the Experimental Process of Different Parameters on the Wicking Property of Tubular Braids

To investigate the effect of weaving patterns, structural axis, and axial yarn position parameters on the wicking property of the tubular braids, the samples should be examined in different groups specified in Table 2. According to Table 2, to determine the weaving pattern, the results of the twelve specimens in these three groups should be the same.

Figure 5 shows the height-time diagram of the liquid wicking over 30 min for all of the braided samples. Therefore, not only determines the weaving pattern but also distinguishes the two other parameters on the wicking property.

The liquid penetration phenomenon in all the braided structures goes through the same process. In all the braid structures under wicking test, first the liquid penetrates into the braided structure at a high speed. Therefore, the height-time diagram has a steep increasing slope. With the gradual decrease in the amount of permeated liquid, the speed of the slope of the diagram decreases.

However, for better comparison of the braided structures, the result of the wicking test at the end of 30 min for all of the specimens is shown in Fig. 6.

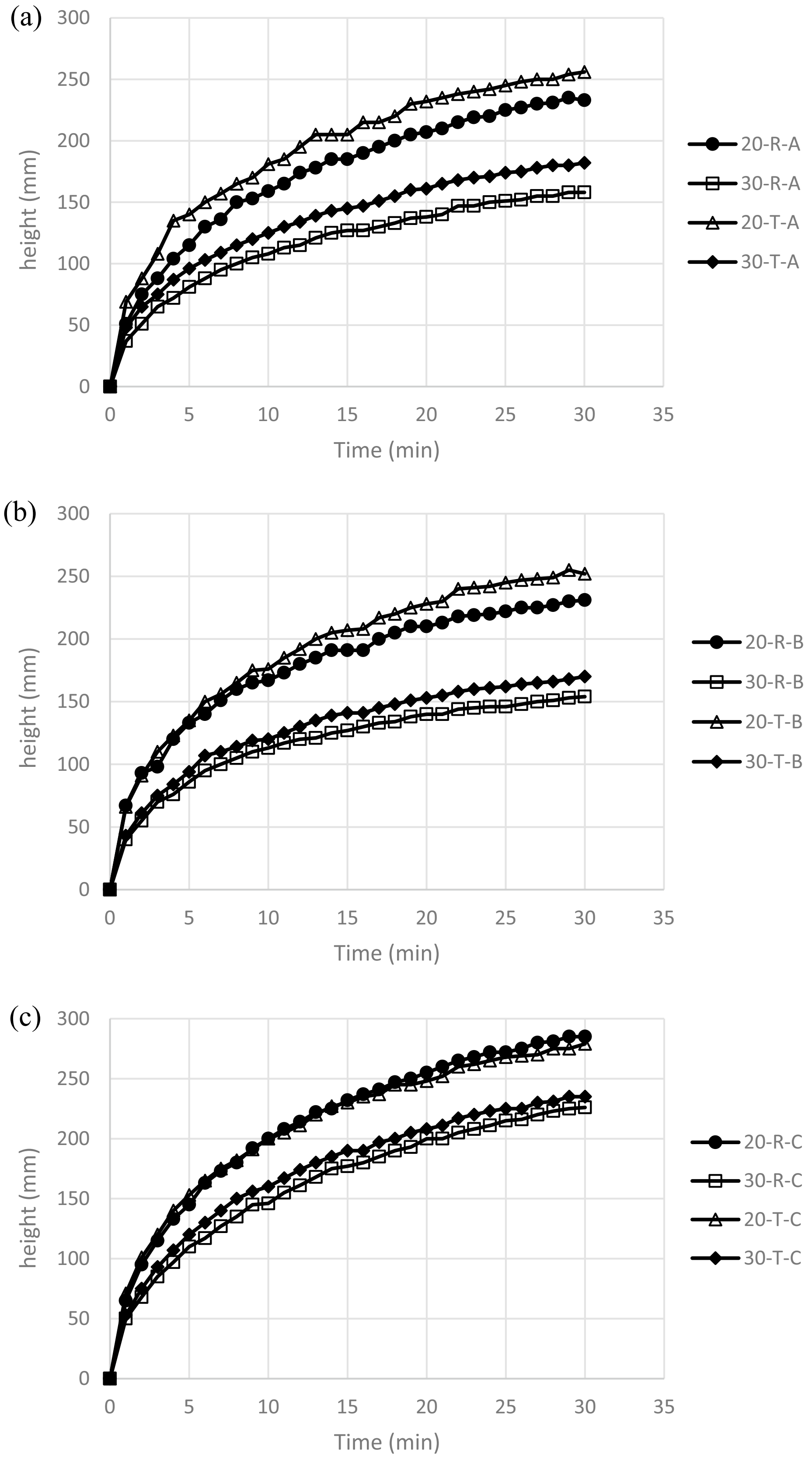
3.1.1 Effect of Weave Pattern

Obviously, as time increases the wicking property has a greater effect on a tubular braid structure and leads to more

Table 2 Classifications of samples for comparison

Group	Sample code	Comparative parameters	Factors
1	20-R-B 30-R-B 20-T-B 30-T-B	Weave pattern: regular, two over two braid angle: 20, 30	Weave pattern braid angle
	20-T-A 30-T-A 20-R-A 30-R-A	Weave pattern: regular, two over two braid angle: 20, 30	Weave pattern braid angle
	20-T-C 30-T-C 20-R–C 30-R–C	Weave pattern: regular, two over two braid angle: 20, 30	Weave pattern braid angle
2	20-R-A 30-R-A 20-R-B 30-R-B	Structural axis: biaxial, triaxial braid angle: 20, 30	Structural axis braid angle
	20-T-A 30-T-A 20-T-B 30-T-B	Structural axis: biaxial, triaxial braid angle: 20, 30	Structural axis braid angle
3	20-R-A 30-R-A 20-R–C 30-R–C	Axial yarns position: core-filled biaxial, triaxial braid angle: 20, 30	Axial Yarns position braid angle
	20-T-A 30-T-A 20-T-C 30-T-C	Axial yarns position: core-filled biaxial, triaxial Braid angle: 20, 30	Axial yarns position braid angle

Fig. 5 Height-time diagram of the liquid wicking. **a** Triaxial Braids, **b** Biaxial Braids, **c** Core-Filled Biaxial Braids



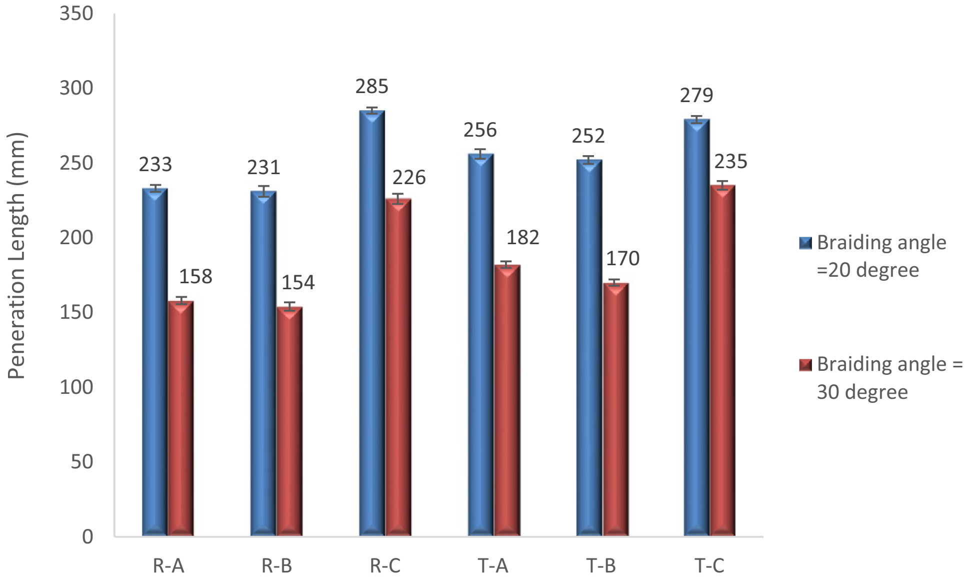


Fig. 6 Liquid wicking results of samples

liquid is absorbed by the structure. This is quite clear in Figs. 5, 6. But the weaving pattern and the braiding angle affect the liquid wicking and the amount of liquid absorbed. Increasing the braid angle in all specimens reduces the liquid wicking into the braid structure. The increase in the braid angle leads to an increase in the distance of the yarns from the braid's axis and placing them obliquely in a braided structure. Therefore, the reduction in the capillary phenomenon causes reduced liquid wicking. A Two over Two pattern also has more liquid wicking than the regular pattern. Basically, a regular weave pattern has less surface weave than a Two over Two weave pattern. Therefore, the liquid wicking is facilitated into the capillary tubes that are formed between the fibers at the cross section of the yarns in a braid which is formed by the Two over Two pattern.

In addition, according to the results, it can be stated that the braiding angle is more effective than the weaving pattern design. In such a way that the braid sample with the Two over Two weaving pattern and braiding angle equal to 20 degree has the maximum liquid wicking. The braid with regular weaving pattern and braiding angle of 20 degree is in the second place. The braid samples with a braiding angle of 30 degree and with the Two over Two and regular weaving pattern have the third and the last rank, respectively.

3.1.2 Effect of Structural Axis

Due to the groupings presented in Table 2, to recognize the effect of the structural axis of the braid, biaxial and triaxial braids should be compared in two different groups. It should be noted that each of them has the same weaving pattern.

According to the results of liquid penetration after 30 min in biaxial and triaxial samples without core in Fig. 5a, b, it can be said that there is not a significant difference between the biaxial and triaxial braids in the same braiding angle. But in the biaxial and triaxial braids, the liquid wicking is reduced with an increase in the braid angle. Therefore, the braid angle is more effective than the number of braid's axial structures.

3.1.3 Effect of Axial Yarns Position

To distinguish the effect of axial yarns position in a braided structure as axial yarns or core yarns, the biaxial braids with core were compared with the triaxial braids.

The results shown in Figs. 5, 6 represent that the sample with core yarns and braid angle equal to 20 degree has the highest liquid wicking. While the sample with axial yarns and braid angle equal to 30 degree has the lowest liquid wicking. The second place belongs to the sample with axial yarns and braid angle equal to 20 degree, and the third-place belongs to the sample with core yarns and braid angle equal to 30 degree. Also, the fluid permeability in the structure of the core braids is higher than the triaxial braids.

As can be seen, the most effective of the tubular braid’s structural parameters on the wicking behavior belongs to the braid angle. The structural axis of the braid does not have a significant effect among the parameters of the braid. Also, the other parameters which are studied are less effective than the braid angle.

3.2 The Ranking of the Different Parameters on the Wicking Property of Tubular Braids

Since the test method is so straightforward and accessible to manipulate, statistical analysis is essential in the design of the experiment to study and comprehend the effects of parameters and their synergistic effects. Moreover, statistical study leads to grouping the specimens based on their performance and as a result a better evaluation of how the parameters affect the wicking property. The one-way analysis of variance with a 95% confidence level is performed on experimental, and the results shown in Table 3.

As can be seen, not only there is a significant difference in the levels of the various parameters mentioned but also the braiding angle has the most effect in wicking. The statistical analysis was carried out and grouped the specimens with the SNK method. It should be noted that this method is suitable for parameters that have more than three variable levels. Otherwise, it only shows the difference. Therefore, only a comparison can be made between the parameters:

weaving patterns: Regular < Two over Two
structural axis: Biaxial < Triaxial
axial yarn position: Axial < Core

In the other hand, for a more accurate diagnosis, a concession is assigned to each sample to determine the most satisfactory braided specimen at wicking characteristics.

The samples with the lowest and highest amount of water penetrated into them receive the lowest and highest points, respectively. The obtained results are listed as follow in Table 4. It is clear that the lowest and highest amount of water infiltration into the samples means the highest and lowest resistance of their structure against liquid penetration, respectively. Therefore, in the case of braided sutures, the priority is to choose the sample that had the least amount of penetration.

4 Conclusion

In this work, a simple capillary rise test method was employed to study the wicking property of the tubular braid's structure made from polyester. Since the purpose of the study was to measure the speed of liquid penetration, it was necessary to minimize moisture absorption in the fiber. Effects of the tubular braid's structural parameters which are included braid angle, interlacement pattern, structural axis (biaxial and triaxial), and the position of the yarns parallel to the axis (axial or core), were discussed. The statistical results and experimental results are in good agreement and show that each of the studied parameters is significant and has affection on the braided structures' wicking behavior. The following conclusions accentuate the importance of suturing structurals' selection. With the increase in the braid angle, the wicking height of a braided structure decreases. Under the same braid angle, the wicking height of a braided structure with the Two over Two weaving pattern is higher than the regular one. The presence of core yarns in the braided structure increases liquid wicking. The number of structural axes does not make a significant difference in liquid wicking. In other words, the wicking property in a biaxial braid is not much different from a triaxial braid. Therefore, wicking in braids is very complicated, and the mechanism has not been fully understood. Nevertheless, this research attempts to gain insight into this area and construct a framework for further study. Modeling of wicking in more complicated structures will form the subject of subsequent research. This paper not only can help to choose suitable parameters to produce the braided sutures but also can be developed in the future and

Table 3 One-way analysis of variance table with 95% confidence

Source	df	Sum of squares	Mean square	F
Pattern	1	1261.500	1261.500	630.750
Angle	1	281530500	281530500	14076.750
Position	2	14404.000	7202.000	3601.000
Pattern*angle	1	20.167	20.167	10.083
Pattern*position	2	532.000	266.000	133.000
Angle*position	2	892.000	446.000	223.000
Pattern*angle*position	2	105.333	52.667	26.333
Error	12	24.000	2.000	
Total	23	45392.500		

Table 4 The result of ranking the samples

30-R–C	20-R–C	30-R-B	20-R-B	30-R-A	20-R-A	Code
5	12	1	6	2	7	Rank
30-T-C	20-T-C	30-T-B	20-T-B	30-T-A	20-T-A	Code
8	11	3	9	4	10	Rank

lead to new products of sutures with wound healing prediction ability.

Since the wicking behavior in a braid structure is a complicated behavior, this paper has made an attempt to better understand of liquid penetration in the braid structures. Further research effort is needed to predict the amount of liquid penetration in the braided structures.

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Data availability All data relevant to the study are included in the article.

Declarations

Conflict of interest All authors declare that they have no conflicts of interest.

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