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Tensile and Knot Performance of Polyester, Silk, Polypropylene and Polydioxanone Sutures

Polyester, İpek, Polipropilen ve Polidiaksanon Ameliyat İpliklerinin Mukavemet ve Düğüm Performansı

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TENSILE AND KNOT PERFORMANCE OF POLYESTER, SILK, POLYPROPYLENE AND POLYDIOXANONE SUTURES

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ABSTRACT: Suture is a generic term for all materials used to bring served body tissues together and to hold these tissues in their normal position until healing takes place. The success of a suture is generally linked to its mechanical performance such as tensile and knot strength. Extensive research has been done on sutures, the majority of which focuses on tissue response to sutures, mechanical properties, knot properties, wound infection and degree of absorption. In this study, it is aimed to investigate the mechanical performance (tensile and knot strength) of materials such as polyester (PES), silk, polypropylene (PP) and polydioxanone (PDO). The obtained results showed that the mechanical performances of sutures are affected by sutures materials, sutures size and knot type. The developed model (tenacity 95 (cN/tex) and elongation 85 (%)) expresses with rather high accuracy the relation between independent variables and dependent variable and that experimental work results were acceptable as accurate.

Keywords: Monofilament suture, braided suture, granny knot, knot strength, tensile performance**.**

POLYESTER, İPEK, POLİPROPİLEN VE POLİDİAKSANON AMELİYAT İPLİKLERİNİN MUKAVEMET VE DÜĞÜM PERFORMANSI

ÖZET*:* Ameliyat iplikleri, vücut dokularını iyileşme sağlayana kadar dokuları bir arada tutmak için kullanılan genel bir terimdir. Bir ameliyat ipliğinin başarısı genel olarak çekme ve düğüm mukavemet performansı ile değerlendirilebilir. Ameliyat iplikleri ile yapılan çalışmaların çoğu düğüm özellikleri, yara enfeksiyonu ve dokunun ameliyat ipliğine vermiş olduğu tepki üzerine yapılmıştır. Bu çalışmada, polyester (PES), ipek, polipropilen (PP) ve polidiaksanon (PDO) ameliyat ipliklerinin mekanik performansının (çekme ve düğüm mukavemeti) araştırılması amaçlanmıştır. Elde edilen sonuçlar gösteriyor ki ameliyat ipliğinin cinsi, boyutu ve düğüm şekli mekanik performans değerlerini etkilemiştir. Model (Mukavemet 95 (cN/tex) ve Uzama 95 (%) bağımlı değişkenler ile bağımsız değişkenler arasındaki ilişkiyi yüksek doğrulukla açıklayabilmekte ve deneysel çalışma verilerini hatasız olarak kabul etmektedirler.

Anahtar Kelimeler: Monofilament ameliyat ipliği, örgülü ameliyat ipliği, granny düğüm, düğüm mukavemeti, mekanik performansı**.**

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1. INTRODUCTION

Suture is a generic term for all materials used to bring served body tissue together and to hold these tissues in their normal position until healing takes place. Sutures which are used in surgical purpose for field of medical textiles now a most demand in joining of different type of tissues. Sutures are used to re-approximate the divided tissues and ligation of the cut end vessels. If the suture fails to perform the above said functions, the consequences may be disastrous. Massive bleeding may occur when the suture loop surrounding a vessel is disrupted. Securing wounds is possible by knot or by recently developed barbed suture. Sutures require knots so as to ensure optimal tissue closure strength. The goal of wound closure is to bring the edges of the wound together not only with sufficient strength to prevent dehiscence, but also with a minimal residual tension and compression of the tissue [1,6].

Hockenberger and Karaca, (2004) is characterized knot performance of monofilament and braided polyamide (PA) sutures by applying two different knots with two, three or four throws. It is observed that granny knot and braided structure have better knot performance. An additional throw does not increase the force required to break the suture. Suture size is also important for knot performance and the sutures behave differently when they are wet [7]. Gemci and Ulcay, (2004) is firstly reviewed some properties about absorbable and non-absorbable sutures. The knot strength differences between normal cat-cut and chromium cat-cut in respect to suture number have been investigated [4]. Marturello and et.al (2013), are evaluated knot security of eleven suture material, 5 knot size (2,3,4,5 and 6 throws), 2 surgeons each tied 6 knots (n=12 for each knot size in 11 suture materials). All knots are incubated in healthy canine donor plasma at 40 ºC for a minimum of 24 hour. Sutures are evaluated for knot security (knot untied, suture failed by breaking, suture slipped from the clamps, or suture untied before testing) and maximum load carried before knot slippage or knot failure (termed tensile failure load) [8]. Abdessalem S.B and et. al. (2009), are presented an experimental procedure for the measurement of mechanical parameters and knot slippage of braided sutures made of polyester fiber. The effect of braid angle on tensile and knot performance was studied, and a slippage ratio obtained from load-extension curves was defined. The variation of braid angle had an important influence on breaking load and elongation of the suture [9]. Heward and et.al. (2004), are conducted tensile performance of non-knotted and knotted non-sterile polyamide (PA), polyvinylidene fluoride (PVDF) and polyether-ester (PEE) sutures by different test conditions (gauge length, test speed, any knot and suture material). Descriptive statistics (Statistical Package for Social Sciences version 10.1.3, SPSS) are calculated for each data set. A logarithmic transformation of the data is used in the ANOVA for tenacity because of the presence of unequal variances, and Tukey's multiple compares procedure is used [10]. Chu C.C. (1980), is used seven commonly suture materials. They are Dexan (poly-glycolic acid), Vicryl (copolymer of glycolide and lactide), surgical silk, Nurolan (Nylon 66), Ethilon (Nylon 66), Mersilene (Polyester) and Prolene (PP), Ethilon and Prolene are in monofilament form, Dexon, Vicryl, Silk, Nurolan and Mersilene are in braided form. Tensile properties of all suture materials are determined on a Instron Tensometer. Nurolon, Ethilon and Prolene are in one group and have the lowest yield stress (0,34-0,52 GPD), Dexon and Vicryl are in the middle while Mersilene and Silk have the highest yield stress (1,20-1,33 GPD) [5].

In this study, the effect of structural parameters on mechanical response of knotted and un-knotted sutures was studied. The difference of this study from the previous studies are applying test method by wearing gloves like in a operating room in a hospital and selection the number of throws in a sterile surgery conditions to the mostly used commercial sutures according to the recommendations of operation surgeon whose working in Gaziantep University Hospital. And also a model is developed by using the Design Expert Analysis of Variance (ANOVA) software. The aim of this model is demonstrating accuracy between independent variables and dependent variables and acceptance of experimental work results.

2. MATERIAL AND METHODS

2.1. Material

Four commonly used in Gaziantep University Hospital non-absorbable suture materials were used. They were Atromat® S2553/2 Poliester (PES), Atromat® R3032 Silk, Dagsan® Polypropylene (PP) and Dagsan ® Polydioxanone (PDO). These sutures are selected according to purchasing manager data's which is requested by operation surgeons. PES and Silk are braided in form, PP and PDO are monofilament. Not only the material but also the physical structure and size of the sutures affect their mechanical behavior. Therefore, we choose two kinds of braided and two kinds of monofilaments structure. We also tested three different United States Pharmacopoeia (USP) sizes (1/0, 2/0, and 3/0) for each suture type. Table 1 shows the properties of sutures used throughout this study.

Table 1. Technical Properties of the Tested Sutures

Materials	**Polyester**			**Silk**			**Polypropylene**			**Polydioxanone**		
USP No	*1/0*	2/0	3/0	1/0	2/0	3/0	1/0	2/0	3/0	1/0	2/0	3/0
Yarn Linear Density (tex)	*121*	113	54	*132*	100	51	110	80	40	130	109	48
Origin	Synthetic			Natural			Synthetic			Synthetic		
Type	Non-absorbable			Non-absorbable			Non-absorbable			Non-absorbable		
Structure	Braided			Braided			Monofilament			Monofilament		
Surface Coating	Silicone			Silicone			None			None		
Sterilization	Ethylene oxide			Ethylene oxide			Ethylene oxide			Ethylene oxide		

2.2. Methods

The experiments were carried out in two stages. At the first stage, it is investigated the tensile and knot strength of all sutures before inserting in physiologic solution. The tensile properties of all sutures are carried out on the TİTAN Universal Tensile Tester before and after inserting physiologic solution according to USP 881; Tensile Strength of Surgical Suture on a Motor Driven Tensile Strength Testing Machine Using Constant Rate of Extension (CRE) Tester standard under controlled laboratory conditions [11]. Prior the tests, suture materials were conditioned prior to testing by placing them in a conditioning chamber of constant temperature (21.1 ºC ± 1.1ºC) and humidity (65 % ± 2%) for 24 hours. They are tested under the same conditions. All tests were repeated five times. During the tests, sutures are clamped in between one fixed jaw and one moving jaw of the Titan and pulled until they broke. The distance between the jaws are 200 mm, and the gauge speed of the Titan is 200 mm/sec. According to the standard, we used a CRE which is 200 mm/min. The 200 mm gauge length is mentioned in Titan Universal Tester's technical report and USP standard. In the tests, maximum tenacity values are obtained. The means of the data are determined.

In the knot strength tests, granny knot is chosen as most of the Turkish surgeons use this type[7]. A knot is composed of a combination of a sequential throws. A single simple granny knot was tied in the middle of each suture, which is two ends of the suture are wrapped together at an angle of 360º (Figure 1). Three throws are necessary for granny knot to reach knot break regardless of the suture size. In order to have the same knot tension in all samples, the knots are tied mechanically on the Titan by applying 10 N tensions [7,13]. Non-sterile latex gloves were worn whenever handling suture materials during the tests.

For the second stage, the sutures are inserted in physiologic solution for 24 hours. This physical solution is 0.9 % isotonic Sodium Klorur (NaCl) at 4-9º C temperature. It is mostly used during and after the surgery. The sutures are also prepared in two forms as in the initial experiments; unknotted and knotted.

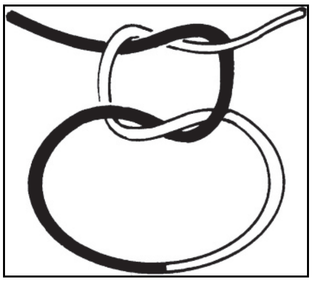


Figure 1. Granny knot [12]

3. RESULTS AND DISCUSSION

3.1 Tensile results of braided and monofilament for un-knotted sutures

In Table 2, tensile results of un-knotted braided and monofilament sutures tested in this study are displaced. For all the suture size, as suture size is increasing, the tensile strength and elongation is decreasing at both braided and monofilament form. For braided sutures (PES-USP1 and Silk-USP1), the lesser number of fibers in cross section are contributing to the breaking load. Inter fiber pressure which leads to build up of frictional resistance owing to an increase in transverse forces causes dominance of fiber slippage. Therefore, suture strength is high by a higher percentage of damage in the form of ruptured fibers. A strong correlation can also obtain with elongation and yarn number. The force necessary for elongation depends on cross sectional fiber bundle. For monofilament sutures, this behavior can be explained by yarn linear density. While yarn linear density is decreasing, the tensile behavior is also decreasing because of decreasing of number of fibers in yarn diameter.

PES has the highest dry tensile strength (7823 cN/tex) and wet tensile strength (4785 cN/tex) while silk has the lowest dry tensile strength (4893 cN/tex) and wet tensile strength (2931 cN/tex) for non-absorbable braided sutures. In other words, tensile strength values of PES sutures are better than silk sutures. In absorbable monofilament from, tensile strength of PP sutures are higher than PDO sutures. In terms of elongation values, PP and PDO exhibit the highest values for dry conditions (28.24 and 37.94 %, respectively), PES and silk exhibit the lowest values for wet conditions (2.66 and 9.61 %, respectively).

Table 2. Tensile Results of Un-knotted Sutures

Un-Knotted Form					
		Dry		Wet	
Suture	**USP No**	**Max.Tenacity (cN/tex)**	**Max.Elongation (%)**	**Max.Tenacity (cN/tex)**	**Max.Elongation (%)**
PES	**1/0**	7823	11.56	7785	07.21
	2/0	4065	11.46	4009	06.15
	3/0	2993	8.68	2057	02.66
SILK	**1/0**	4893	17.23	2931	10.32
	2/0	2388	13.66	1843	09.11
	3/0	1400	11.54	1144	07.68
PP	**1/0**	7761	28.24	5171	13.32
	2/0	2790	23.61	1776	12.01
	3/0	1972	17.68	996	11.21
PDO	**1/0**	5860	37.94	4030	21.20
	2/0	3202	13.76	1329	09.65
	3/0	2081	11.13	1274	08.66

3.2. Tensile results of braided and monofilament for knotted sutures

In Table 3, tensile results of knotted braided and monofilament sutures tested in this study are displaced. Wet knot performance of sutures is very important as they are in wet state after operation throughout healing. Therefore, the wet tensile properties are also performed to complete the knot performance analysis. It is observed that the force necessary to break the knot are about 41 % (tenacity) and 35% (elongation) lower for wet sutures compared to dry state as water causes reduction in strength and elongation for most materials. This reduction is slightly more for the braided sutures and the finest size.

Silk is defined as protein polymer and therefore is aqua highly affected by absorption. Thus, we assume that aqua absorption from the body also plays an important role in strength reduction.

PES sutures are not highly affected in aqueous conditions. PES has hydrocarbon backbones, which contain ester linkages, and are hydrophobic in nature. Therefore, these sutures are not affected by aqua. While USP 1/0 sized polyester sutures have highest tenacity, USP 3/0 sized ones have the lowest strength values. PES has the higher tensile strength with 6010 cN/tex than silk with 3437 cN/tex tensile strength for non-absorbable braided sutures. In absorbable monofilament from, PP is stronger tensile strength with 5571 cN/tex than PDO with 4371 cN/tex tensile strength. In terms of elongation values, PP and PDO exhibit higher values (15.77 and 31.38 %, respectively) than PES and silk (6.09 and 3.00 %, respectively) for knotted sutures.

At the same time, the failure of sutures occurred at the knot rather than along the suture strand. This behavior indicates the knot causes an area of high stress concentration. Because, the suture strand in the knot may be weakened during knot formation and as the strand is drawn out during loading. And also, tightening of the knot and the friction between the suture strands in the knot may contribute to the failure. Therefore, the differences between un-knotted and knotted suture specimens may provide useful information on which to base a choice of knot stability and strength. Similar results are obtained by A.S.Hockenberger et al. [7,13], who tested knot performance of synthetic, non-absorbable polyamide sutures. Other studies have reported that the knot is the weakest part of any suture or ligature when subjected to tension [5,8,9].

Table 3. Tensile Results of Knotted Sutures

Knotted Suture								
Suture	**USP No**	**Number of Throw**	**Dry**		**Wet**			
			Max. Tenacity (cN/tex)	**Max. Elongation (%)**	**Max. Tenacity (cN/tex)**	**Max. Elongation (%)**	**Reduction Tenacity (Dry-Wet) %**	**Reduction Elongation (Dry-Wet) %**
PES	**1/0**	**1**	6010	10.38	5274	06.09	62.18	41.33
		3	4221	09.14	3980	05.80	53.00	36.54
	2/0	**1**	3379	10.39	2871	05.71	44.66	45.04
		3	2228	07.56	2025	03.99	35.91	47.22
	3/0	**1**	2221	07.22	2209	04.82	60.11	33.24
		3	1094	05.13	985	03.86	31.26	37.03
SILK	**1/0**	**1**	3437	05.92	1630	03.00	52.57	49.32
		3	2826	05.07	1371	02.86	51.49	43.59
	2/0	**1**	2013	03.42	1159	01.09	42.42	68.13
		3	1264	01.13	1024	01.00	18.99	11.50
	3/0	**1**	895	03.65	582	02.13	34.97	41.64
		3	631	02.10	593	02.11	06.02	00.48
PP	**1/0**	**1**	5571	15.77	2089	09.57	62.50	39.32
		3	4053	10.22	1580	08.76	61.02	14.29
	2/0	**1**	3361	13.87	1057	07.10	68.55	33.89
		3	2296	11.60	1287	06.12	43.95	38.62
	3/0	**1**	1326	10.23	1063	5.85	19.83	43.27
		3	1607	09.40	1084	4.36	32.55	35.83
PDO	**1/0**	**1**	4371	31.38	2369	20.34	45.80	35.18
		3	3349	26.81	2075	18.29	38.04	31.78
	2/0	**1**	2158	17.75	1821	14.87	15.62	16.23
		3	1870	17.02	1432	12.43	23.42	26.97
	3/0	**1**	1446	11.30	657	07.30	54.56	35.40
		3	1056	09.37	693	05.19	34.38	44.61
						Average	41.41	35.40

4. STATISTICAL SIGNIFICANCE ANALYSIS

The experimental results have also been statistically evaluated by using the Design Expert Analysis of Variance (ANOVA) software with F values of the significance level of α = 0.05, with the intention of exploring whether there is statistically significant difference between the variations obtained. We evaluated the results based on the F-ratio and probability of F-ratio (prob>F). The lower the probability of F-ratio, it is stronger the contribution of the variation and the more significant the variable. The best models for each fabric were obtained and the corresponding regression equations and regression curves were fitted. The test results of the related fabrics were entered into the software for the analysis of the general design.

Table 6 summarizes the statistical significance analysis for all the data obtained in the study. In the table, variables are suture raw materials (PES, silk, PP, PDO), test conditions (dry and wet), USP No (1/0), 2/0 and 3/0), structure (knot and un-knotted) and number of knot throws (1 and 3). Moreover, abbreviations in Table 4: F-V is the F-Value, A- Suture Raw Material, B- Test Conditions, C-USP No and D-Structure, E- Number of Knot, R_a^2 –Adjusted R^2 and R_p^2- Predicted R^2. Here, the p values of models smaller than 0.05 are considered to be significant. The ANOVA table also indicates the significant interactions between tenacity and elongation. The term A, B, C, D and E in this table is independent variables, whereas the tensile properties are dependent parameters. The term “model” is the sum of the model terms in the ANOVA table. The regression equations were also developed by considering the ANOVA table. And also, a 2FI design was suggested by the software for tensile behavior of sutures (Table 4 and 5).

When ANOVA table (Table 6) is examined, it can be seen that suture raw materials, test conditions, USP No, structure and number of knot throw have significant impact on tenacity and elongation values. In addition, according to the table, the R^2 value of the model turned out to be approximately 0.95 for tenacity and 0.85 for elongation. In this case, terms in the model can explain the model at 95 and 85 % ratio. This case shows that the model created (Equation 1 and Equation 2) for response values (tenacity (cN/tex) and elongation (%)) can express with rather high accuracy the relation between independent variables and dependent variable and that experimental work results were acceptable as accurate.

Table 4. Model summary statistics (tenacity)

Source	**Standard Deviation**	**Adjusted R^2**	**Predicted R^2**	
Linear	773.43	0.8198	0.7921	Aliased
2FI	**362.74**	**0.9710**	**0.9576**	**Suggested**
Quadratic	305,81	0.9435	0,9351	Aliased
Cubics	175.51	0.9776	0.9724	Aliased

Table 5. Model summary statistics (elongation)

Source	**Standard Deviation**	**Adjusted R^2**	**Predicted R^2**	
Linear	5.46	0.3223	0.4784	Aliased
2FI	**3.21**	**0.8901**	**0.8392**	**Suggested**
Quadratic	3.51	0.8624	0.8817	Aliased
Cubics	2.11	0.9771	0.9549	Aliased

Table 6. Statistical significance analysis of Tenacity (ANOVA table)

	Tenacity (cN/Tex)			**Elongation (%)**		
Source	**F-V**	**Prob > F**		**F Value**	**Prob > F**	
Model	57.76	< 0.0001	Significant	18.00	< 0.0001	Significiant
A	*37.15*	*<0.0001*	Significiant	57.96	< 0.0001	Significiant
B	*303.47*	*<0.0001*	Significiant	71.62	< 0.0001	Significiant
C	*446.10*	*<0.0001*	Significiant	31.78	< 0.0001	Significiant
D	*270.83*	*<0.0001*	Significiant	23.89	< 0.0001	Significiant
E	*47.83*	*<0.0001*	Significiant	13.69	0.0003	
AB	*10.92*	*<0.0001*	Significiant	12.17	< 0.0001	Significiant
AC	*6.01*	*<0.0001*	Significiant	25.47	< 0.0001	Significiant
AD	*1.64*	*0.3411*		4.65	0.0060	
BC	*31.72*	*<0.0001*	Significant	5.76	0.0042	
BD	*2.95*	*0.0967*		12.92	0.0007	
CD	*57.68*	*<0.0001*	Significant	8.70	0.0004	
ACD	*3.71*	*0.0040*		3.49	0.0043	
R^2	0.9752			0.9270		
R_a^2	0.9884			0.8045		
R_p^2	0.9370			0.7705		

Tenacity = $2614.93+521.11*A-720.28*B+1651.42*C+531.72*D-280.18*E-313.09*AB + 179.79*AC+112.66*AD-450.63*BC-0.57*BD+608.44*CD+83.94*ACD$ (1)

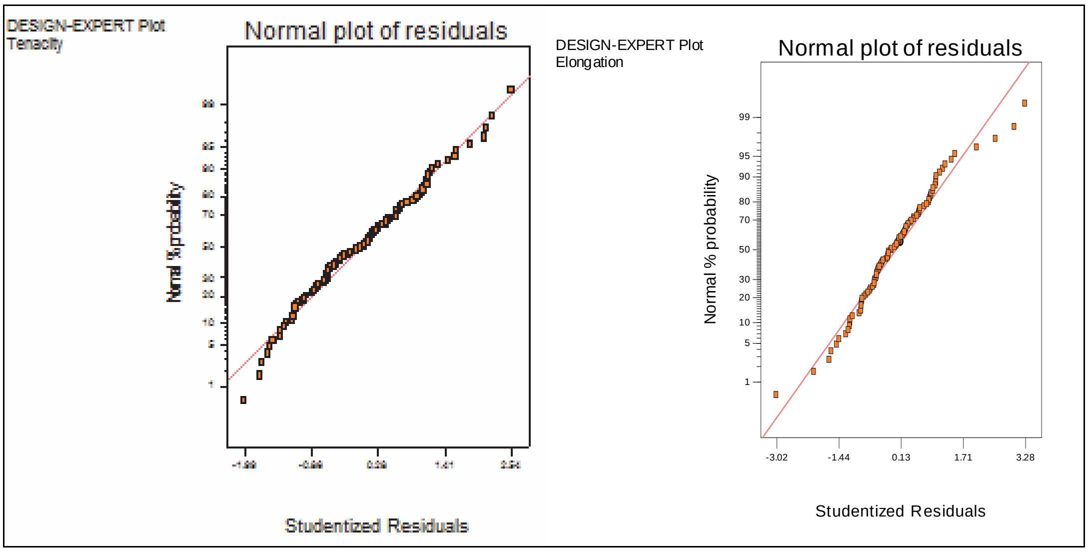
Elongation = $11.99-4.50*A-2.54*B+3.18*C+1.46*D-1.15*E+0.29*AB-1.91*AC-0.99*AD-1.45*BC-1.07*BD+1.75*CD-1.59*ACD$ (2)

A normality test (normal distribution test) was also applied on the data obtained from tensile behavior by changing suture (PES, Silk, PP, PDO), test conditions (dry and wet), USP No (1/0, 2/0, 3/0), structure (knot and un-knot) and number of knot throw (1 and 3). The results are demonstrated in Figure 2. In general probability plotting is a graphical technique for determining whether sample data conform to a hypothesized distribution based on a subjective visual examination of the data. The assessment is very simple. From the data, which are scattered around the normality line as shown in Figure 2, we can see that they conform to normal distribution. This analysis also supports the conformity of chosen model.

The prediction performance of the generated regression model has been evaluated in Table 7 and 8. In these tables, actual values of tenacity and elongation obtained from experimental test results and the prediction made by the statistical model are demonstrated. The tables include Absolute Percentage Error (APE %) values of each prediction and Mean Absolute Percentage Error (MAPE %) values in order to see the prediction capacity of the model. APE of each prediction can be calculated as

$$APE = \left(\left|\frac{A_i - B_i}{A_i}\right| \times 100\right) \quad (3)$$

Here A_i is actual value, P_i is predicted values, I is the number of the experimental point. For instance, according to ANOVA analysis sequence, selecting Suture 1, PES USP No 1/0 dry test conditions, knotted and number of throw is 1; the actual tenacity is 6010 cN/Tex. The predicted tenacity by the statistical model developed is 5127.54 cN/Tex. The APE is calculated as 14.68 %. The MAPE value, which is an important parameter in assessing the prediction performance of the model, is also given in the Tables. It is calculated as 1.48 % in Table 7 (tenacity), and 2.82 % in Table 8 (elongation) for the generated statistical model and these mean that value of the investigated fabrics can be predicted with 98.52 % (tenacity) and 97.18 % (elongation) confidence by using the developed models. In addition, the correlation coefficient of the statistical model for evaluating of the chosen fabrics is illustrated in Table 6. The correlation coefficient of the model was found as 97.52 % for tenacity and 92.70 % for elongation according to ANOVA Table. And these show that the parameters chosen as suture type, test conditions, USP No, structure and number of knot throws explain the 98 % (tenacity) and 93 % (elongation) of the variability in tensile behavior.



a b

Figure 2. Normality test for tensile performance of samples (a. Tenacity, b. Elongation)

Table 7. Predictions made by statistical model and its prediction performance (tenacity (cN/Tex))

Suture	Actual Tenacity (cN/Tex)	Predicted values	APE (%)	Suture	Actual Tenacity (cN/Tex)	Predicted values	APE (%)
1	6010	5127.54	14.68	**49**	4221	4880.65	15.63
2	3437	3242.88	05.65	**50**	2826	2995.98	06.01
3	5571	4624.33	16.99	**51**	4053	4377.44	08.00
4	4371	4134.13	05.42	**52**	3349	3887.23	16.07
5	2273	2363.35	03.97	**53**	1984	2116.46	06.68
6	1630	1636.02	00.37	**54**	1371	1389.13	01.32
7	2089	2269.06	08.62	**55**	1580	2022.17	27.99
8	2369	2194.77	07.35	**56**	2075	1947.88	06.13
9	3379	3142.26	07.01	**57**	2228	2895.36	29.95
10	2013	1703.59	15.37	**58**	1264	1456.70	15.25
11	3361	2713.05	19.28	**59**	2296	2466.16	07.41
12	2158	2325.09	07.74	**60**	2871	2146.27	11.13
13	1870	1554.64	16.86	**61**	1423	1307.74	08.10
14	1159	1273.30	09.86	**62**	1024	1026.41	00.24
15	1057	1534.34	45.16	**63**	1287	1287.45	00.03
16	1821	1562.30	14.21	**64**	1432	1315.41	08.14
17	2221	1953.01	12.07	**65**	1094	1706.11	55.95
18	895	0811.34	09.35	**66**	0631	0564.45	10.55
19	1326	1780.30	34.26	**67**	1607	1533.41	04.58
20	1446	1265.34	12.49	**68**	1056	1018.45	03.56
21	2209	2794.15	13.05	**69**	0752	0523.49	30.39
22	582	0786.05	35.06	**70**	0593	0539.16	09.08
23	1063	1006.59	05.31	**71**	1084	0759.70	29.92
24	657	0907.55	38.14	**72**	693	0660.66	04.67
25	7823	7974.81	01.94	**73**	782	7727.92	01.22
26	4893	5004.15	02.27	**74**	4893	4757.25	02.77
27	7761	7932.35	02.21	**75**	7761	7685.46	00.97
28	5860	6203.40	05.86	**76**	5860	5956.50	01.65
29	7785	7783.05	01.99	**77**	4785	4633.19	03.17
30	2931	3066.75	04.63	**78**	2931	2819.85	03.79
31	5171	5246.54	01.46	**79**	5171	4999.65	03.31
32	4030	3933.50	02.39	**80**	4030	3686.60	08.52
33	4065	4117.03	01.28	**81**	4065	3870.14	04.79
34	2388	2619.36	09.69	**82**	2388	2372.47	00.65
35	2790	3161.07	13.30	**83**	2790	2914.18	04.45
36	3202	2935.61	08.32	**84**	3202	2688.72	16.03
37	4009	4197.82	09.72	**85**	2004	1951.97	02.60
38	1843	1858.53	00.84	**86**	1843	1611.64	12.55
39	1776	1655.82	06.77	**87**	1776	1404.93	20.89
40	1329	1842.28	38.62	**88**	1329	1595.39	20.04
41	2993	2883.53	03.66	**89**	2993	2636.64	11.91
42	1400	1573.36	12.38	**90**	1400	1326.47	05.25
43	1972	2159.57	09.51	**91**	1972	1912.68	03.01
44	2081	2145.11	03.08	**92**	2081	1898.22	08.78
45	2054	2374.86	35.14	**93**	1014	1123.47	10.80
46	1144	1217.53	06.43	**94**	1144	0970.64	15.15
47	996	1055.32	05.96	**95**	0996	0808.43	18.83
48	1274	1456.78	14.35	**96**	1274	1209.89	05.03
MAPE (%)	01.48						
R (%)	98.52						

Table 8. Predictions made by statistical model and its prediction performance (elongation (%))

Suture	Actual Elongation (cN/Tex)	Predicted values	APE (%)	Suture	Actual Elongation (cN/Tex)	Predicted values	APE (%)
1	10.38	10.21	01.61	**49**	09.14	09.28	01.49
2	05.00	05.86	01.73	**50**	05.07	04.93	02.78
3	15.00	15.81	05.39	**51**	10.22	14.87	45.52
4	31.00	28.12	09.30	**52**	26.81	27.18	01.38
5	06.00	06.38	06.39	**53**	05.80	05.45	06.08
6	03.00	03.04	01.20	**54**	02.86	02.10	26.57
7	09.00	06.62	26.47	**55**	08.76	05.68	35.14
8	20.00	20.87	04.35	**56**	18.29	19.93	08.99
9	10.00	09.77	02.31	**57**	07.56	08.83	16.84
10	03.00	01.18	60.63	**58**	01.13	00.25	78.29
11	13.00	12.99	00.10	**59**	11.60	12.05	03.89
12	17.75	17.14	03.46	**60**	17.02	16.20	04.82
13	17.02	10.45	38.59	**61**	03.99	09.52	13.51
14	01.09	02.86	16.82	**62**	01.00	01.93	92.89
15	09.00	08.31	07.68	**63**	07.12	07.37	03.55
16	14.00	14.40	02.86	**64**	12.43	13.46	08.32
17	07.00	06.45	07.85	**65**	06.13	05.51	10.04
18	03.00	03.01	00.17	**66**	02.10	02.07	01.46
19	20.00	18.32	08.38	**67**	16.30	17.39	06.67
20	11.00	11.05	00.47	**68**	09.37	10.12	07.96
21	04.00	04.98	24.52	**69**	03.86	04.04	04.79
22	02.00	02.54	26.78	**70**	02.11	01.60	24.18
23	11.00	11.49	04.48	**71**	10.46	10.56	00.92
24	07.00	06.16	11.94	**72**	05.19	05.23	00.73
25	11.00	13.26	20.58	**73**	11.00	12.33	12.07
26	17.00	17.32	01.88	**74**	17.00	16.38	03.63
27	28.00	27.50	01.79	**75**	28.00	26.56	05.13
28	37.00	34.97	05.49	**76**	37.00	34.03	08.02
29	07.21	05.88	18.42	**77**	07.21	04.95	31.40
30	10.32	10.94	05.98	**78**	10.32	10.00	03.09
31	13.32	14.76	10.78	**79**	13.32	13.82	03.75
32	21.20	24.17	14.00	**80**	21.20	23.23	09.58
33	11.46	10.71	06.56	**81**	11.46	09.77	14.73
34	11.77	12.34	04.87	**82**	11.77	11.41	03.08
35	13.61	15.43	13.40	**83**	13.61	14.50	06.52
36	13.76	15.32	11.32	**84**	13.76	14.38	04.51
37	06.15	07.84	27.45	**85**	06.15	06.90	12.23
38	10.11	10.47	03.59	**86**	10.11	09.54	05.67
39	08.09	07.12	10.97	**87**	08.09	06.27	22.54
40	09.65	09.03	06.44	**88**	09.65	08.09	16.13
41	08.68	08.65	00.35	**89**	08.68	07.71	11.13
42	11.54	13.05	13.12	**90**	11.54	12.12	05.01
43	27.68	25.11	09.30	**91**	27.68	24.17	12.68
44	11.13	14.58	31.03	**92**	11.13	13.65	22.62
45	02.66	03.63	36.33	**93**	02.66	02.69	01.15
46	09.61	09.03	06.02	**94**	09.61	08.10	15.76
47	11.21	14.72	31.32	**95**	11.21	13.78	22.97
48	08.66	06.14	29.07	**96**	08.66	05.21	39.88
MAPE (%)	02.82						
R (%)	97.18						

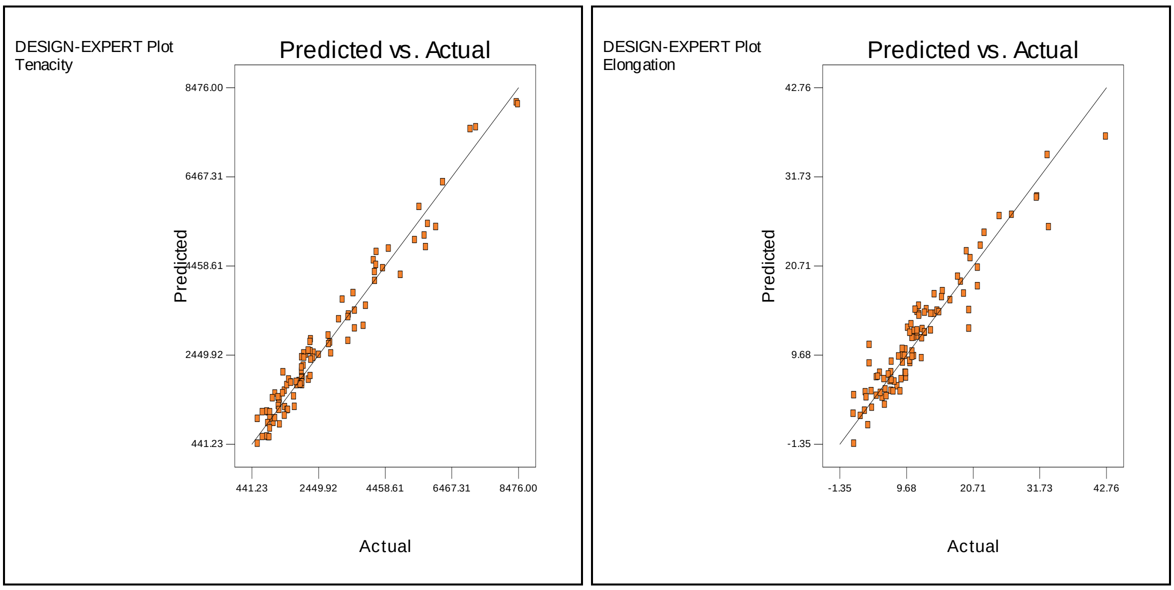
The prediction performance of the model developed can be seen clearly in Figure 3. This figure demonstrates comparative diagrams between the real tensile behavior and the predictions made by the statistical model successively. Here, the tensile behavior results and predictions made the model are marked on the figure according to sequence in Table 7 and 8. The predictions made by the statistical model are scattered around actual tenacity and elongation values, as seen from the Figure 7.

5. CONCLUSIONS

The choice of the correct suture is fundamental for tissue healing and patient recovery. This choice usually takes into account not only type of wound, tissue characteristics but also typical physical characteristics such as tensile strength, knot strength, elasticity and diameter. For this reason, in this study, tensile performance of four commonly used USP size suture materials are observed at dry and wet conditions. These behaviors may also be a valuable additional concerning sutures overall performance by surgeons. These experimental data suggest to the surgeons for specific end uses. For example, judging from the mechanical properties, due to high tensile strength, PES and PP sutures can be considered to use for cardiovascular surgery and prosthesis. Because these two body parts need more force for closing surgical wounds while having severe edema. Due to the swelling of these wounds, sutures must be enough strength without causing deformation or destruction of tissue. Especially PP sutures have high strength and elongation values. If the suture is elongated, it can be permanently deformed. When the tissue is reverted, suture should be fully recovered to its original dimensions. Therefore, a suture with high strength and elongation like PP can be suitable for cardiovascular surgery and prosthesis. However, for sensitive surgery operations like eye tissues do not need extra strength like cardiovascular surgery and prosthesis. Therefore, PDO and silk can be used for micro and eye surgery having large elongation capacity such as skin and muscle. In addition, polymer scientists would have a basic ground for the future development of sutures of improved properties.

The obtained results generally showed that the mechanical performances of sutures are affected sutures materials (PES, Silk, PP and PDO), sutures size (USP 1/0, 2/0 an 3/0), testing conditions (dry and wet) and number of knot throws (1 and 3) as can be advised operation surgery.

Further work will focus on the study of tissue reactions, wound conditions and knot security along with suture's mechanical properties. It would also be useful to study test conditions; for example gauge length and test speed.



a b

Figure 3. The comparative diagram of the actual and predicted values by the statistical model a. tenacity, b. elongation

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