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Comparison of tensile and knot security properties of surgical sutures

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Abstract Sutures are classified into non-absorbable and absorbable, and mechanical properties of these materials vary by the composition. Knotting induces decrease in mechanical properties. The objective of this study was to measure the tensile and knot security properties depending on the type and caliber of sutures. Changes in properties after tensile loading were measured with absorbable sutures. Tensile properties such as maximum tensile load, elongation rate, stiffness and energy absorbed before breakage of seven kinds of surgical sutures were measured. Absorbable sutures were immersed in 37 °C Hank's balanced salt solution up to 14 days under the tensile load of 100 g/thread, and properties were measured again. Knot was formed with surgeon's knot method, and tensile properties were measured. Five specimens were tested for each condition. Values were analyzed with one- or two-way analysis of variance ($\alpha = 0.05$). Maximum tensile load of seven sutures (caliber = 4-0) ranged from 10.0 N to 14.3 N. In non-absorbable sutures, the type of suture material influenced the tensile properties ($P < 0.05$). In absorbable sutures, the maximum tensile load after tensile loading decreased, which was significant in chromic catgut (CC). Knot security of seven sutures (caliber = 4-0) ranged from 8.7 N to 11.9 N. Type of non-absorbable suture influenced knot security ($P < 0.05$), and the synthetic monofilament materials showed a tendency to be untied easily. Since no single suture material possesses all of the requirements, proper type and caliber suture should be selected based on this study.

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Introduction

Suturing is performed for varied purposes in surgical field. Primary closure of tissues, which were separated by surgical procedure or accidental trauma, promotes a healing process and controls inactive bleeding [1]. The materials used for this purpose include sutures, tissue adhesives and stapler, which are termed as suture materials. Among these suture materials, suture is the most commonly used material; therefore, a suture material generally indicates a suture. Ideal suture materials should satisfy several requirements [2]. They should have high tensile strength but lose strength at the same rate as the tissue gains strength, and should be easy to handle and form secure knots. They should be biologically inert; therefore, they should induce minimal tissue inflammation and should not promote infection. They should be able to stretch, accommodate wound edema and recoil to its original length with wound contraction. Since no single suture material possesses all of these features, it is the practitioner's task to weigh the advantages and disadvantages of the available suture materials.

Various sutures are used clinically, and they are classified by several criteria: (1) spontaneous degradation—absorbable and non-absorbable; (2) composition—natural and synthetic; and (3) structure—monofilament and multifilament [2, 3]. An advantage of absorbable sutures is that they generally do not require removal. However, these materials incite varying degrees of tissue response due to their degradation by hydrolysis, enzymatic digestion or phagocytosis [4]. The speed of this hydrolysis depends on the temperature and the pH of the tissue or the liquids surrounding the suture material [5]. Proteolytic enzymes in the body digest catgut suture material. Other synthetic absorbable sutures are absorbed via hydrolytic degradation. Enzymatic degradation elicits more reaction than do hydrolytic reactions in the body [6].

Natural and synthetic sutures are used. Natural sutures such as silk and catgut are largely being replaced by synthetic materials. A further subdivision of sutures is monofilament and multifilament. Multifilament suture materials consist of several filaments twisted or braided together, which gives good handling and tying qualities. Monofilament sutures have some advantage such as lower knot tie-down resistance, lower tissue drag and less risk of infection compared with braided type suture materials. They resist the harboring microorganisms and ties smoothly, which can ease the judgment of the tightening of a knot. However, because they have relatively higher bending stiffness and the tendency to untie, it is hard to deal with it and to form stable knot [7, 8]. In addition, their stiff cut ends could irritate mucosa and cause ulceration. In contrast to monofilament sutures, multifilament sutures give good handling and tying qualities because they have lower bending stiffness and are easy to form a stable knot. But, their braided structure could offer nidus for food debris or bacteria, which can be a latent infection source [9].

Besides knot untying, suture breakage after knotting is another common problem. The effect of knotting on the strength of various sutures was studied [10], and concluded that knotting a suture reduced the tensile strength. In addition, it has been demonstrated that knot security is a function of knot configuration including the number of throws used to make the knot as well as the size and type of suture material [11]. Practitioners should strive to tie the most secure knot while keeping knot bulk to a minimum with the suture material most ideally suited for the task at hand. Knot security was measured with varied protocols [12, 13].

As to the thickness of sutures, caliber denotes the diameter of the material. Stated numerically, the more zeroes in the number, the smaller the size of the strand. For example, 00000 is referred to as 5–0, which is smaller than caliber 4-0 [14].

Varied sutures are used in surgical procedures, and they have different mechanical properties. Their properties change in sutured condition, in which condition they are subject to tensile loading. Also knot security may vary by the type of sutures. However, there have been few studies on the changes in mechanical properties of surgical sutures after tensile loading and on the knot security of these materials in the same experimental condition. The null hypotheses of the present study were (1) tensile properties of surgical sutures were not different depending on the type of material, (2) tensile properties of absorbable surgical sutures did not change after storage under tensile loading condition, and (3) knot security of surgical sutures was not different depending on the type of material. The objective of this study was to measure the tensile properties and knot security depending on the type and caliber of sutures. Changes in tensile properties after tensile loading were measured in absorbable materials. Evaluated tensile properties were maximum tensile load, elongation rate, stiffness, and energy absorbed before breakage.

Material and methods

Sutures

Among non-absorbable sutures, silk (SL), nylon (NL), polyester (PE) and polypropylene (PP) were investigated. Plain catgut (PC), chromic catgut (CC) and braided polyglycolic acid suture (PGA) were investigated among absorbable sutures (Table 1).

Measurement of tensile properties at the baseline

Five specimens of 85 mm in length were prepared for each material. Tensile properties were measured using a universal testing machine (4465, Instron, Norwood, MA) with proprietary grip devices. Gauge length was 75 mm and cross head speed was 5 mm/min.

Load-displacement curve was obtained from the machine, and maximum tensile load (N), elongation rate (%), slope of the load-displacement curve (stiffness, N/mm) and energy absorbed before breakage (N·mm) were calculated from this curve (Fig. 1). Stiffness was calculated using a manual method by connecting two points on the straight portion of the load-displacement curve. Energy absorbed before breakage was calculated by the integration of the area under the load-displacement curve.

Effect of storage under tensile loading on the change in tensile properties of absorbable suture material

In case of absorbable suture materials, 100 g load was applied to each suture thread under the condition of immersion in 37 °C Hank's balanced salt solution. After storage for 1, 3, 5, 7 and 14 days, tensile properties were measured.

Measurement of knot security

Knot was formed with the surgeon's knot method (two turn clock-wise, one anticlock-wise and one clock-wise with 3 mm cut ends) by pulling the material with the tensile load of 1 kg. Knot was aligned in the center of gauge

Table 1 Suture materials tested in this study

Type	Code	Brand name	Composition	Batch number	Manufacturer
Non- Absorbable	NL	Nylon	Monofilament nylon	NB434	AILEE Co. Ltd., Korea
	PE	Polyester	Silicone coated braided polyester	PEG4291TDN	AILEE
	PP	Polypropylene	Monofilament polypropylene, Polyolefin	PP426	AILEE
	SL	Silk	Silicone treated braided organic protein (fibroin)	SK426P	AILEE
Absorbable	CC	Chromic catgut	Purified connective tissue (mostly collagen)	C429	AILEE
	PC	Plain catgut		P426R	AILEE
	PGA	Surgifit	Braided polyglycolic acid	AV4391	AILEE

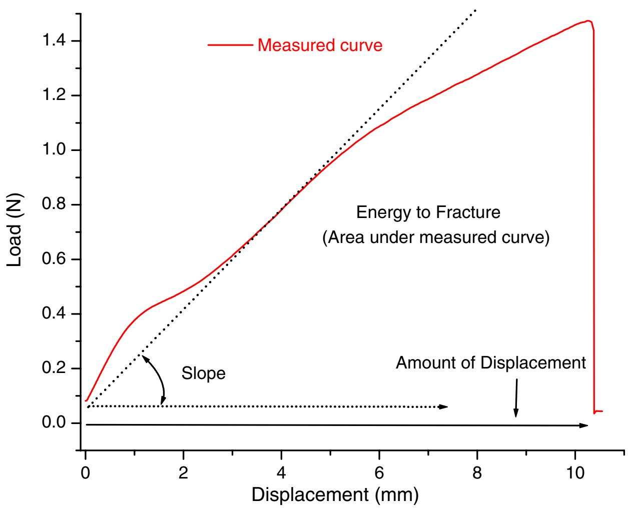

Fig. 1 Calculation of slope, elongation and energy to fracture

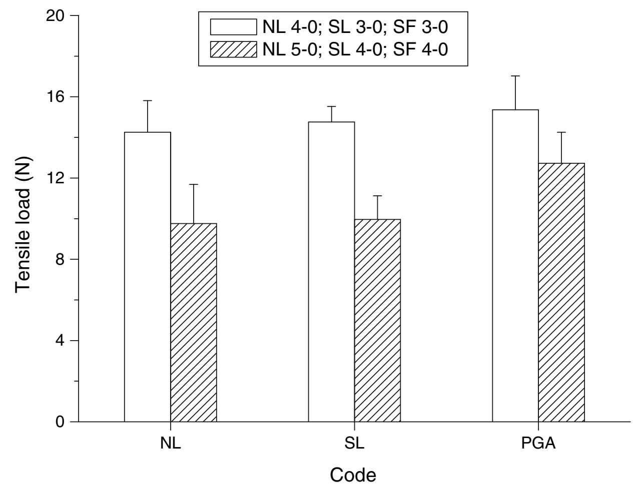

Fig. 2 Comparison of maximum tensile loads (N) for suture materials with different calibers

length, and tensile properties were measured with the gauge length of 75 mm and the cross head speed was 5 mm/min. It was determined whether suture material was fractured, or knot was slipped.

Statistical analysis

The influence of the type of suture material (caliber = 4-0) on the tensile properties and knot security was analyzed by one-way analysis of variance (ANOVA) at the significance level of 0.05. Means were compared with Fisher's Protected Least Significance Difference (PLSD) interval. After storage under tensile load, the influence of suture material and storage period was analyzed by two-way ANOVA. To determine whether the immersion period and tensile properties have correlation, simple linear regression analysis was performed.

Results

Comparison of maximum tensile loads by the caliber of sutures is presented in Fig. 2. When caliber increased, maximum tensile load decreased.

Tensile properties of sutures (caliber = 4-0) at the baseline are listed in Table 2. Maximum tensile load was in the range of 10.0–14.3 N; elongation rate was in the range of 7.3–22.0%; stiffness was in the range of 0.8–1.7 N/mm; and energy before breakage was in the range of 33.7–125.2 N·mm.

Since the application field and properties of non-absorbable and absorbable sutures are different, the influence of the type of suture materials on the tensile properties was analyzed within each group of non-absorbable or absorbable sutures. Within non-absorbable sutures under the condition of the same caliber of 4-0, the type of suture significantly influenced the maximum tensile load, elongation rate, stiffness and energy absorbed before breakage based on one-way ANOVA. Fisher's PLSD interval was 0.68 N for the maximum tensile load, 1.23% for the elongation rate, 0.10 N/mm for the stiffness, and 8.97 N·m for the energy absorbed before breakage. Within absorbable sutures under the condition of the same caliber of 4-0, the type of suture significantly influenced the stiffness, but did not influence the maximum tensile load, elongation rate and energy absorbed before breakage based on one-way ANOVA. Fisher's PLSD interval was 0.71 N for the

Table 2 Tensile properties of suture materials at the baseline (caliber = 4-0)

Code	Tensile load (N)	Elongation rate (%)	Stiffness (N/mm)	Energy to break point (N·mm)
NL	14.3 (1.6)*	22.0 (1.1)	1.7 (0.4)	89.7 (12.7)
PE	10.8 (1.0)	9.3 (0.6)	1.3 (0.1)	42.3 (4.5)
PP	11.7 (0.5)	21.7 (3.1)	0.8 (0.0)	125.2 (19.1)
SL	10.0 (1.2)	7.3 (0.9)	1.3 (0.0)	33.7 (9.5)
CC	12.4 (1.1)	14.8 (2.1)	1.2 (0.1)	75.0 (10.6)
PC	12.9 (0.5)	15.2 (0.5)	1.1 (0.0)	82.4 (5.7)
PGA	12.7 (1.5)	13.5 (2.1)	1.5 (0.1)	78.5 (21.1)
Interval**	0.68	1.23	0.10	8.97

* Standard deviations are in parentheses

** Fisher's protected least significant difference (PLSD) interval by the type of suture material ($P < 0.05$)

maximum tensile load, 1.08% for the elongation rate, 0.04 N/mm for stiffness and 8.88 N·m for the energy absorbed before breakage.

Correlation between the maximum tensile load and the energy absorbed before breakage is presented in Fig. 3. Regardless of non-absorbable and absorbable sutures, the maximum tensile load and the energy absorbed before breakage had significant correlation at the significance level of 0.05, and the correlation coefficient (r) was 0.60. In case of PP, the energy absorbed before breakage was high even though the maximum tensile load was lower than others.

Changes in tensile properties of absorbable sutures (caliber = 4-0) after storage under tensile loading are listed in Table 3. Maximum tensile load and energy absorbed before breakage was influenced by the type of material and immersion period, and there was significant interaction between two variable based on two-way ANVOA ($P < 0.05$). In case of elongation rate, type of material did not influence the value, but immersion period influenced the value, and there was significant interaction between two variable ($P = 0.05$). In case of stiffness, type of material influenced the value, but immersion period did not influence the value, and there was significant interaction between two variable ($P = 0.05$).

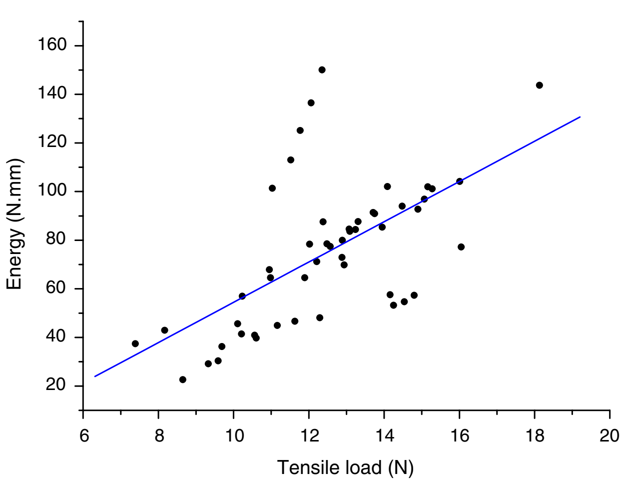

Fig. 3 Correlation between the tensile load and the energy up to fracture at the baseline

After storage under tensile loading, simple linear regression analysis between storage period and tensile load was performed. As the result, in case of CC, there was weak correlation between storage period and tensile load ($r = -0.440$, $P = 0.014$). However, in case of PC and PGA, there was no significant correlation.

Knot security of suture materials (caliber = 4-0) at the baseline are listed in Table 4. When the caliber of the suture materials was the same as 4-0, the type of non-absorbable suture influenced the knot security (maximum tensile load), elongation rate, stiffness and energy absorbed before breakage based on one-way ANOVA. Fisher's PLSD interval was 0.74 N for the maximum tensile load, 1.49% for the elongation rate, 0.16 N/mm for the stiffness and 13.15 N·m for the energy absorbed before breakage. When the caliber of the suture materials was the same as 4-0, the type of absorbable suture did not influence the maximum tensile load, elongation rate, stiffness and energy absorbed before breakage based on one-way ANOVA at the significance level of 0.05. Fisher's PLSD interval was 1.68 N for maximum tensile load, 1.77% for the elongation rate, 0.15 N/mm for the stiffness and 15.84 N·m for the energy absorbed before breakage. Monofilament suture materials showed a tendency to be untied easily. Although polyester suture material is braided type, it had a slight tendency to be untied.

Suture failures of non-absorbable sutures took place mostly via slippage of the knot, and resulted in catastrophic failure. All of the five specimens of NL material showed knot slippage, but PE and PP showed both types of failure modes. However, in case of absorbable suture materials, all suture materials were broken before knots were untied.

Comparison of the maximum tensile load of suture materials and knot security is presented in Fig. 4. Maximum tensile loads decreased after knotting. Regardless of non-absorbable and absorbable sutures, the maximum tensile load and the knot security had significant correlation at the level of 0.05, and the correlation coefficient (r) was 0.52.

Table 3 Changes in tensile properties of absorbable suture materials after immersion in HBSS at 37 °C (caliber = 4-0)

Code	Duration	Tensile load (N)	Elongation rate (%)	Stiffness (N/mm)	Energy to break point (N·mm)
CC	0	12.4 (1.1)*	14.8 (2.1)	1.2 (0.8)	75.0 (10.6)
	1 D	9.3 (1.3)	13.3 (1.7)	1.0 (0.1)	47.6 (12.7)
	3 D	9.9 (1.0)	12.6 (1.4)	1.2 (0.1)	47.1 (10.0)
	5 D	9.9 (2.0)	12.7 (2.0)	1.1 (0.1)	50.4 (16.8)
	7 D	10.6 (0.9)	13.8 (1.6)	1.1 (0.2)	55.1 (8.7)
	14 D	8.6 (1.3)	10.6 (2.2)	1.2 (0.2)	36.2 (9.5)
PC	0	12.9 (0.5)	15.2 (0.5)	1.1 (0.0)	82.4 (5.7)
	1 D	10.7 (1.2)	11.6 (1.1)	1.3 (0.1)	48.7 (10.0)
	3 D	11.2 (0.6)	14.1 (1.6)	1.2 (0.2)	57.8 (7.8)
	5 D	10.9 (1.7)	12.8 (2.1)	1.3 (0.1)	53.8 (16.6)
	7 D	12.5 (0.6)	14.1 (0.8)	1.4 (0.0)	66.3 (6.7)
	14 D	10.3 (0.5)	13.3 (0.6)	1.2 (0.1)	52.7 (3.3)
PGA	0	12.7 (1.5)	13.5 (2.1)	1.5 (0.1)	78.5 (21.1)
	1 D	14.5 (0.5)	14.5 (0.9)	1.6 (0.1)	97.0 (7.1)
	3 D	14.6 (0.6)	15.1 (0.8)	1.5 (0.0)	102.4 (8.8)
	5 D	13.7 (1.5)	13.7 (1.8)	1.5 (0.0)	88.4 (21.2)
	7 D	15.0 (1.6)	14.9 (2.0)	1.4 (0.2)	104.2 (25.4)
	14 D	13.1 (1.2)	11.6 (2.1)	1.5 (0.5)	69.6 (22.9)
Interval-1**		0.31	0.42	0.04	3.63
Interval-2		0.43	0.59	0.05	5.13

* Standard deviations are in parentheses

** Interval-1: Fisher's protected least significant difference (PLSD) interval ($P < 0.05$) by the type of material; Interval-2: Fisher's PLSD interval ($P < 0.05$) by the immersion period

Table 4 Knot security of suture materials at baseline (caliber = 4-0)

Code	Knot security–maximum tensile load (N)	Elongation rate (%)	Stiffness (N/mm)	Energy to break point (N·mm)
NL	11.9 (1.6)*	24.0 (2.5)	1.1 (0.2)	102.9 (20.7)
PE	10.1 (1.0)	11.0 (1.5)	1.4 (0.4)	33.7 (21.0)
PP	9.7 (1.2)	22.7 (3.5)	0.6 (0.1)	101.9 (28.5)
SL	10.4 (0.5)	8.6 (1.3)	1.6 (0.3)	38.8 (7.1)
CC	9.7 (1.1)	11.7 (2.2)	1.1 (0.1)	47.7 (15.7)
PC	8.7 (2.0)	12.1 (2.7)	1.1 (0.2)	46.8 (19.1)
PGA	9.2 (4.0)	14.6 (3.3)	1.3 (0.4)	63.1 (35.6)
Interval**	1.2	1.6	0.2	14.4

* Standard deviations are in parentheses

** Fisher's protected least significant difference (PLSD) interval by the type of suture material ($P < 0.05$)

Discussion

The first null hypothesis of the present study was rejected in non-absorbable suture materials, but was accepted in absorbable suture materials because the type of non-absorbable suture significantly influenced the four tensile properties, but the type of absorbable suture influenced the stiffness, but did not influence the maximum tensile load, elongation rate and energy absorbed before breakage. The second null hypothesis of the present study was rejected because the tensile load and energy absorbed before breakage was influenced by the tensile loading period. The third null hypothesis of the present study was rejected in non-absorbable sutures, but was accepted in absorbable sutures because the type of non-absorbable suture material influenced the knot security, elongation rate, stiffness and energy absorbed before breakage, but the type of absorbable suture material did not influence the maximum tensile load, elongation rate, stiffness and energy absorbed before breakage.

Tensile properties of sutures are important for the practitioner making a knot. If the material is too weak and the knotting force is stronger than tensile strength of suture material, suture can easily break while tightening the knot. Therefore, it is essential to know the tensile strength of sutures [5]. There are many studies on the measurement of the tensile properties of various sutures [4, 8, 15, 16]. Compared to the results of the previous studies, almost all

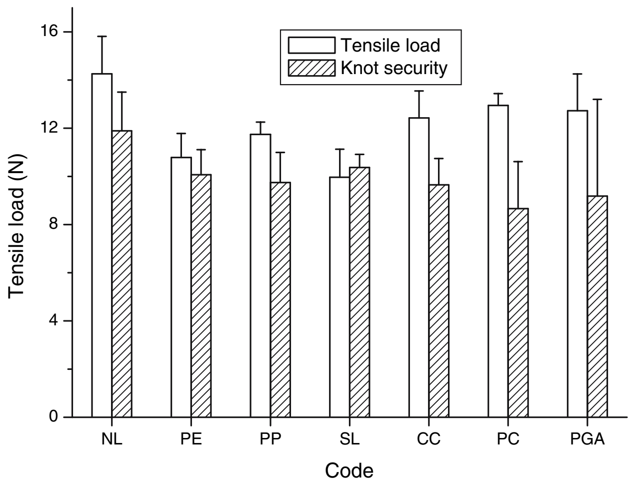

Fig. 4 Comparison of the maximum tensile load and knot security

sutures showed relatively low maximum tensile loads in the present study, which can be explained with several reasons. First, it may reflect the difference in testing methods. In the previous studies, the tensile properties of sutured tissue with multiple sutures were measured, and multiple suturing and the properties of tissues should have influence the maximum tensile loads measured. In the present study, tensile properties of suture materials themselves were measured instead of the measurement of the tensile properties of sutured tendon with multiple sutures [16]. Therefore, tensile loads were lower than those of the previous study: 14.3 N for nylon, 11.7 N for polypropylene, and 10.8 N for polyester in the present study vs. 46.7 N for nylon, 63.4 N for polypropylene, and 65.6 N for polyester in multiple sutured tendon based on the study of Lawrence and Davis [16]. Second, gauge length of the present study was longer and loading rate was slower than those of the previous studies, which might have influenced the maximum tensile load. It has been reported that tensile strength is influenced by the changes in gauge length used for tensile property measurement [17]. Generally, smaller gauge lengths resulted in slightly higher tensile strength values due to the well-known fact that smaller test volumes exhibit less statistically distributed defects and therefore have a lower probability of fracture. And higher values were measured for higher loading rates [17]. In the present study, gauge length was 75 mm and crosshead speed was 5 mm/min. The influence of gauge length and loading speed simulating the clinical condition should be further studied.

In previous studies, tensile loads of nylon, polyester and polypropylene were compared [4, 8, 15, 16], and the results varied depending on the test protocols. Several studies concluded that tensile load of nylon was lower than those of polyester and polypropylene. But others concluded that nylon showed higher tensile load than the others, which are coincident with the results of the present study. In the present study, nylon showed the highest elongation rate of 22.0%, which might have induced the highest tensile load. However, this fact did not mean that more extensible sutures have higher tensile load. The tensile strength of a suture had no correlation with its elongation rate [5], and this fact is confirmed with the present study. In the present study, there was no significant correlation between the maximum tensile load and elongation rate ($P = 0.29$).

There is another factor to be considered. Elongation of suture materials causes gap formation at the suture site, which is regarded as clinical failure. Displacement of suture materials >3 mm is regarded as clinical failure [13]. Therefore, high maximum tensile load of nylon, originated from high elongation rate, might not have clinical benefit because higher elongation rate of nylon can cause clinical failure. Moreover, elongation of suture material causes the decrease in diameter of material, which can act as a knife and can tear tissues. However, higher elongation rate of a suture gives the practitioner who is tightening the knot a better feeling in estimating the breakage point of the thread. Monofilament sutures provide higher elongation rate than braided sutures. In this respect, since nylon has the highest elongation rate, this material may provide a practitioner better feeling.

Absorbable suture material should maintain adequate tensile strength until the tissues could cope with tensile load without suture. Adequate repair tensile strength is governed by not only the suture technique but also the suture material used [16]. Therefore, the choice of proper suture is an important factor with this respect for desirable clinical outcome. All the investigated absorbable sutures showed decrease in the maximum tensile load after tensile loading for 14 days, but it was not statistically significant except for CC. Although proteolytic enzyme was not added to the immersion solution, the maximum tensile load of CC decreased compare to its initial value. Since catgut was known to be degraded by enzymes, not by hydrolysis, the decrease in tensile load might have been induced by other factors such as water sorption [18]. However, the main focus of the present study was not the degradation by solutions, but the change in tensile properties under tensile loading, which simulated the sutured condition. Therefore, continuous tensile load of 100 g was applied to simulate the sutured condition in vivo. This condition could partly explain the significant decrease in the maximum tensile load in solution that did not contain proteolytic enzyme.

In the present study, as expected, the tensile load measured after knotting decreased compare to the baseline value except silk. Silk showed opposite results, but the difference was not significant. This result confirms the results of the previous studies [10, 15]. It was reported that knotting a suture material reduced the maximum tensile load, and the reduction rate was 39% for braided polyester and 24% for nylon [19].

A high load event may result in suture failure in two ways: slippage of the knots resulting in gapping and clinical failure, and catastrophic failure by breakage of the suture material [13]. Both modes of suture failures may be equally important. But barring unauthorized activities, failure, defined as knot slippage of 3 mm or more, may be a more frequent source of unrecognized or late recognized failure after soft tissue repair. Knot slippage and gapping of soft tissue repairs may result in a suboptimal physical environment for healing to occur; therefore, it is prudent to maximize every opportunity for a good repair, including the elimination of mechanical instability of the repair suture. In the present study, monofilament absorbable sutures have been shown to have a significantly increased incidence of knot slippage.

In the present study, suture failures of non-absorbable suture materials mostly took placed via slippage of the knot and catastrophic failure. All of the five specimens of nylon were shown knot slippage, three specimens of the five specimens of polyester and polypropylene were showed knot slippage, but the other two specimens were showed suture breakage. Suture failures of all absorbable sutures took placed only via suture breakage before untying. In the present study, to compare knot security in the same knot configuration, one knotting method was used regardless of the type of sutures, although varied knotting methods could have been applied to promote the breakage of suture without slippage. If different knotting methods were used, different result should have been obtained. Further study on this issue should be performed.

Within the limitations of the present study, the maximum tensile loads of sutures varied by the type and caliber of suture materials. Maximum tensile loads generally decreased after tensile loading, but the decrease was significant only in CC. Mode of knot failure varied by the structure of filament such as monofilament and multifilament. Based on this study, proper type and caliber suture should be selected. Further study on the degradation of sutures under both of tensile loading and enzymatic action should be performed.

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