Theoretical and Experimental Estimation of the Stored Energy of Plain Knitted Fabrics Using Yarn Pullout Test

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ABSTRACT

The yarn pullout test is a suitable method for investigating the internal mechanical properties of the fabric structure which is established during the weaving or knitting process. In this study, a theoretical model is presented to estimate the stored energy of plain-knitted fabrics which is determined using yarn pullout. The model can predict the stored energy in the fabric, based on the fabric dimensional properties of stitch length and yarn contact angle using force balance analysis. Moreover, in order to evaluate the suggested model, three types of plain-knitted fabric from cotton, cotton/polyester and cotton/nylon with three different stitch lengths were produced and subjected to pull-out tests. Comparison between experimental and theoretical results, demonstrates a reasonable prediction. The results show that the cotton/polyester fabric has the maximum stored energy, because of its higher yarn to yarn friction coefficient. It was also found that, the increase in fabric's loop length leads to a decrease in the fabric's stored energy.

Keywords: Yarn pull-out test, stored energy, plain-knitted fabric, stitch length, theoretical model

INTRODUCTION

Among various methods to evaluate a fabric's mechanical characteristics, the yarn pull out test is a practical method to investigate the fabric's internal deformations caused by the constituent yarns. One of the important assumptions in such loading is to consider the fabric as a composite of yarns.

Pullout test is also a method, providing useful information about fabric tearing, its ability to absorb energy especially in ballistic applications, finishing efficiency, bending and shearing hysteresis of the fabric, and finally the frictional behavior of the fabric. In this test, a force is applied to one end of a single yarn of the fabric to pull it out. This sort of loading is not a novel procedure and scholars have applied such tests to examine mechanical behaviors of fabrics [1]. The main usage of the yarn pullout test is to achieve a better estimation of the relaxation state of cotton weft knitted fabrics conferring minimum internal energy due to relaxation treatments. Whereas, the lowest yarn pullout force can be attributed to the minimum internal energy of fabric [2]. Therefore, a full stability of fabric dimensions is accompanied by the lowest yarn pullout force.

Taylor [3] studied fabric tear strength through a yarn pullout test, and represented a theory based on the yarn interactions. Upon his view, the applied load overcomes the frictional force in crossovers and causes the thread to be pulled out of the fabric weave. When the applied load increases, it tears the fabric, because it becomes more than yarn breaking strength.

Sebastianb et al. [4] used the yarn pullout technique to evaluate the effect of a softening agent on fabric performance, and they proposed a simple model to calculate pullout load and the influence of yarns crossing over.

Sebastianb et al. [5] and Motamedi et al. [6] developed physical models based on spring junction's assumptions, to investigate frictional behavior of yarns within the fabrics.

In the field of fabric failure, Realff et al. [7] and Seo et al. [8] focused on the role of yarn-to-yarn friction and the slippage of yarns in crossovers when the woven fabric is applied by a force. They pointed that before fabric failure, the yarn pullout is occurred.
Pan and Young [9] emphasized on geometrical and mechanical properties of fabric and the yarns. Their model was able to predict the maximum pullout force, and found meaningful relations between the pullout force and some important properties of fabrics such as the bending hysteresis, and the tensile compliance.

Pan [10] proposed an analytical model and analysis of fiber pullout from a bonded fibrous matrix. He demonstrated that the model can predict the behavior of fiber pullout in these systems, provide insights on interactions between fibers by means of bonds, characterize bond properties, and reveal and estimate important parameters.

Hosseini and Toriumi [11] demonstrated that the nature of the stick-slip motion of the dynamic-frictional force of a pulled-out thread is periodic and depends on the fabric construction. They also found high correlation between the warp-pullout force, the intensity of thread interaction at the crossing points, the strength of fabric in the warp direction and the weft yarn irregularity.

Badrosamay et al. [12] introduced an oscillation model, which was capable of anticipating yarn pullout force-displacement profile.

Kirkwoods et al. [13] studied yarn pullout process as an energy absorbent and characterized the yarn pullout force and energy as a function of pullout distance through a semi-empirical model.

Jeddi et al. [2] investigated the dimensional properties of plain knitted fabrics produced from cotton yarn and subjected to different relaxation treatments. They characterized the internal energy of fabric by using yarn-pullout test method in ultrasonic relaxation state and compared it with other common mechanical relaxation treatments.

Valizadeh et al. [1] presented a theoretical model to predict variations of the internal mechanical parameters of woven fabrics based on a force-balance analysis of yarn pullout test.

To consider the internal stored energy of plain knitted fabric, which can be attributed to the internal mechanical properties, we suggested a theoretical model in this research. This model can predict the stored energy in the fabric, according to the fabric dimensional properties, stitch length, and contact angle of yarns, using force balance analysis.

THEORETICAL MODEL

In order to simplify the model, we considered the following assumptions:

- Yarn extension during the pullout test is negligible.

- Yarn cross section during the pullout test is constant.

Figure 1 shows a typical force-displacement curve, resulting from yarn pullout test for woven fabrics [1].

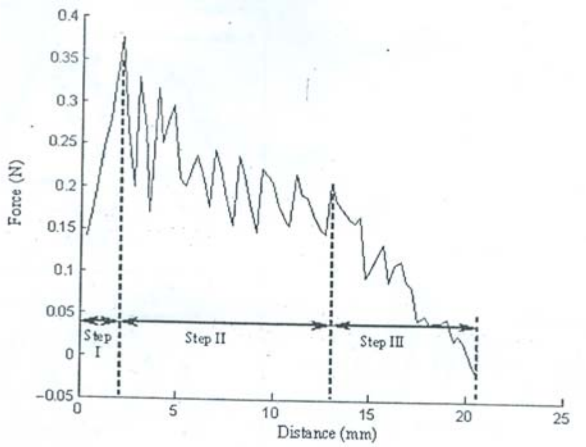

FIGURE 1. General pattern of force-displacement curve resulting from yarn pullout from a woven fabric [1].

The stored energy in the fabric is calculated from the underneath area of the curve as following:

$$W=F.d \tag{1}$$

Where F is the yarn pullout force, and d is the yarn displacement.

Two distinct regions are recognizable from *Figure 1.* In the first region, the force increases to reach to a maximum value, which corresponds to the maximum static frictional force (F_S). The maximum pullout force is due to pullout of two legs of the first loop from the neighbor loops. After overcoming the friction between first loop and neighbor loops at cross points, the yarn pullout curve shows a stick-slip oscillation (second region). This region corresponds to the dynamic frictional force (F_K), which remains almost constant.

Figure 2 shows the yarn pullout test from plain knitted fabric schematically. This figure illustrates that during the yarn pullout, the yarns slip in a circular path on each other. By assuming that the yarn cross section is constant during pullout test, we may use Capstan's law to calculate the pullout force. Capstan's law which is used to calculate the friction between string and pulley is as following:

$$T_1 = T_2 .e^{\mu\theta} \tag{2}$$

Where T_1 and T_2 are input and output tensions respectively, μ is friction coefficient between two yarns and θ is the contact angle of two yarns.

FIGURE 2. Schematic of yarn pullout test from plain knitted fabric.

The stored energy in the fabric during pullout test equals to summation of required energies to unravel each loop. Therefore:

$$W = \sum_{n=1}^{m} \left(F_n . d_n\right) \tag{3}$$

Where F_n is the required force to unravel the nth loop, d_n is the vertical displacement of the yarn, corresponds to unraveling of the nth loop and m is the number of unraveled loops.

Figure 3 shows the yarn pullout process for the plain knitted loops. During the yarn pullout for the first loop, F_1 is the output tension (T_1) and is equivalent to average force in oscillatory region (F_K) of force-displacement curve (*Figure 1*) i.e.:

$$F_1 = T_1 = F_K$$

After unraveling the first loop and dominance on static friction, the required force to unravel the second loop is calculated as following:

$$F_2 = T_2 + F_1 \tag{4}$$

Eq. (4) expresses that, F_2 equals to summation of required force to dominate the dynamic friction of the second loop with underneath loops (T_2) and required force to unravel the previous loop (F_1). Using Capstan's law, T_2 obtains as following:

$$T_2 = \frac{T_1}{e^{\mu\theta_1}} = \frac{F_K}{e^{\mu\theta_1}} \tag{5}$$

Substituting Eq. (5) in Eq. (4) will give:

$$F_2 = \frac{T_1}{e^{\mu\theta_1}} + F_1 = \frac{F_K}{e^{\mu\theta_1}} + F_1 \tag{6}$$

Consequently, F_n is calculated as following:

$$F_n = \frac{T_{n-1}}{e^{\mu\theta_{n-1}}} + F_{n-1} \tag{7}$$

In order to calculate the stored energy in the fabric, using Eq. (3), the values of θ and d should be estimated.

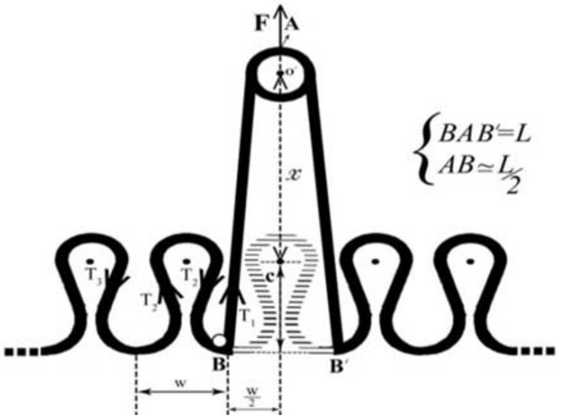

FIGURE 3. Loops unraveling in the plain knitted fabric during the pullout test.

Estimation Of The Contact Angle Of Two Yarns (θ)

As illustrated in *Figure 3*, *BB'*= *w* = wale spacing, and *BAB'*=*L*= loop length. In order to show the detail of the yarn path, a part of *Figure 3* is magnified in *Figure 4*. The circles *O'* and *O* are respectively, the cross section of the needle to pullout the yarn from the fabric and the yarn used in the fabric. It is assumed that, the yarn length between A and B equals to length of the line that connects A to B directly.

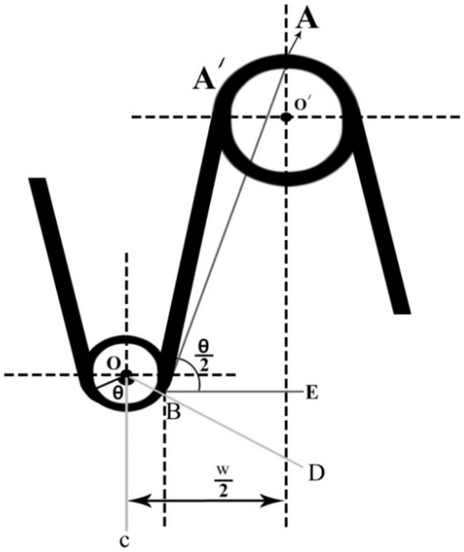

FIGURE 4. Magnified part of *Figure 3*.

Referring to *Figure 4*, $A\hat{B}E$ equals to $C\hat{O}D$ and equivalent to $\frac{\theta}{2}$. Owing to the fact that the yarn diameter is ignorable against wale spacing, thus, it can be written:

$$\tan(\frac{\theta_1}{2}) = \frac{AE}{BE} = \frac{d_1}{w/2} \qquad \Rightarrow \theta_1 = 2tg^{-1}(\frac{2d_1}{w}) \qquad (8)$$

In the next step:

$$\tan(\frac{\theta_2}{2}) = \frac{d_2}{3w/2} \qquad \Rightarrow \theta_2 = 2tg^{-1}(\frac{2d_2}{3w}) \qquad (9)$$

Finally, θ_n is obtained as following:

$$\tan(\frac{\theta_n}{2}) = \frac{d_n}{(2n-1)w/2} \qquad \Rightarrow \theta_n = 2tg^{-1}(\frac{2d_n}{(2n-1)w}) \qquad (10)$$

Estimation Of The Yarn Vertical Displacement (*d*)

Figure 5 shows two continuous stages of unraveling of the first and second loops.

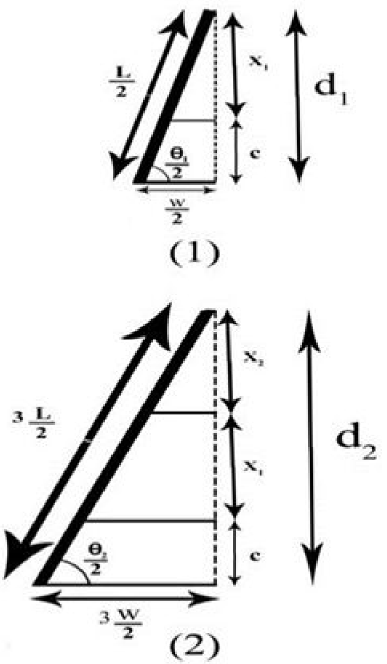

FIGURE 5. Two continuous stages of unraveling of the first and second loops.

In triangle (1), the value of d_1 equals to $x_1 + c$, where c is course spacing. From triangle (1) and (2), the value of x_1 and x_2 can be obtained as follows:

$$(d_1)^2 = (x_1 + c)^2 = \left[(L/2)^2 - (w/2)^2\right] \qquad (11)$$

$$(d_2)^2 = (x_2 + d_1)^2 = (3)^2\left[(L/2)^2 - (w/2)^2\right] \qquad (12)$$

Finally, d_n is calculated as following:

$$(d_n)^2 = (x_2 + d_{n-1})^2 = (2n-1)^2\left[(L/2)^2 - (w/2)^2\right] \qquad (13)$$

By determination of d and θ in different stages of yarn pullout, and replacing them in Eq. (3) and Eq. (7), the stored energy in the fabric will be calculated.

MATERIALS AND METHODS

Three types of plain-knitted fabric from cotton, cotton/polyester and cotton/nylon with three different loop lengths were produced using 30 Ne (20 tex) ring yarn on a circular knitting machine (gauge 28 and diameter 30 inch). The fabric characteristics are given in *Table I*.

TABLE I. Fabric characteristics.

Fabric Code	Description	Course Spacing (cm)	Wale Spacing (cm)
C1	100% Mercerized Cotton Loop Length: 3.18 mm	0.061	0.058
C2	100% Mercerized Cotton Loop Length: 3.3 mm	0.062	0.060
C3	100% Mercerized Cotton Loop Length: 4.66 mm	0.129	0.059
CP1	Mercerized 67% Cotton-33%Polyester Loop Length: 3.18 mm	0.054	0.058
CP2	Mercerized 67% Cotton-33%Polyester Loop Length: 3.3 mm	1.887	0.059
CP3	Mercerized 67% Cotton-33%Polyester Loop Length: 4.66 mm	0.116	0.057
CN1	Mercerized 67% Cotton-33% Nylon Loop Length: 3.18 mm	0.057	0.056
CN2	Mercerized 67% Cotton-33% Nylon Loop Length: 3.3 mm	0.064	0.057
CN3	Mercerized 67% Cotton-33% Nylon Loop Length: 4.66 mm	0.126	0.058

Yarn's Friction Coefficient Measurement

To measure the yarn to yarn friction coefficient, from each bobbin of yarn (cotton, cotton/polyester and cotton/nylon), 12 strings were cut and fixed on two short and long cardboards (*Figure 6*). The components of the used apparatus (the Instron Tensile Tester 5566) included the long cardboard, fitted horizontally on the bottom jaw, the short cardboard weighting 40 gf, an inextensible cord connected to short cardboard, and a low friction pulley. The short cardboard is drawn at a constant speed (5 cm/min) by the Instron-tester crosshead. The principle of the measurements was based on the rectilinear motion of yarns in perpendicular direction.

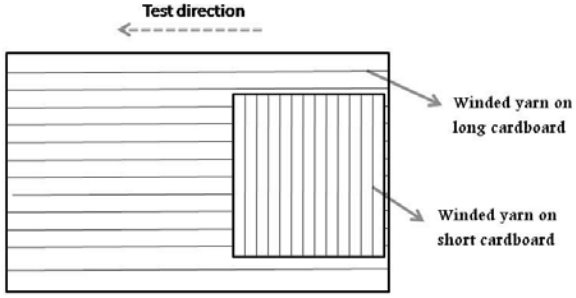

FIGURE 6. Yarn to yarn friction measurement.

This experiment was performed 4 times for each yarn and the static and dynamic friction coefficients were calculated as following:

$$\mu_{s,k} = \frac{F_{s,k}}{\frac{m}{1000} \times 10 \times n} \tag{14}$$

Where *m* is the weight of short cardboard and *n* is the number of yarn strings.

The average results are shown in *Table II.*

TABLE II. Yarns' friction coefficient.

Yarn Type	μ_s	μ_k
Cotton	0.29	0.25
Cotton/Polyester	0.38	0.3
Cotton/ Nylon	0.34	0.27

Yarn Pullout Test

To perform yarn pullout test, fabric samples with 17X7.5 cm dimensions were cut and unraveled in the course direction. The prepared sample was clamped to a U form frame (*Figure 7*). The frame was connected to the lower head of tensile strength tester (Instron 5566). Then, the middle loop of the sample was unraveled from the knit and connected to the upper head of Instron (*Figure 8*). The upper head moved up at a velocity of 20 mm/min and the pullout force was measured while 30 loops were unraveled from the knit. For this purpose 30 loops were counted and marked on the fabric before pullout test. During the test, when the marked loops were unraveled from the knit, the test was stopped. From each fabric structure, five samples were tested and the pullout curves were recorded by using Instron. *Figure 9* illustrates a typical yarn pullout curve.

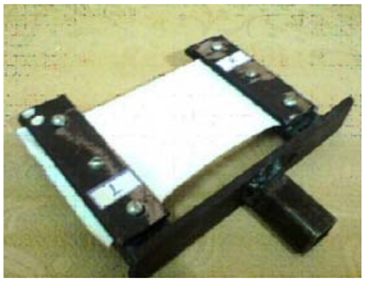

FIGURE 7. Clamped fabric using the U form frame.

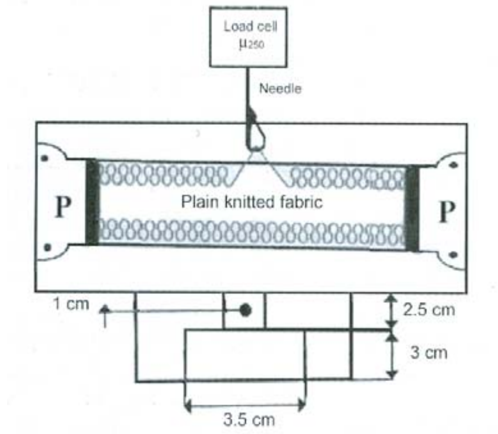

FIGURE 8. Modified tensile tester used to measure the yarn pullout.

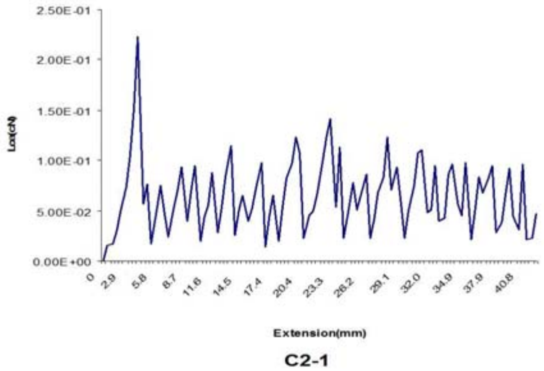

FIGURE 9. Yarn pullout curve from the plain knitted fabric.

RESULTS AND DISCUSSION

In order to calculate the underneath area of the experimental yarn pullout curve, the Cumtrapz tool of Matlab software was used. Also, the stored energy in the fabric calculated theoretically, by replacing θ_n and d_n from Eq. (11) and (14) in Eq. (8) and (3). Since the calculated values of θ for different loops are very close to each other, the average values of θ are shown in *Table III* for different fabric structures.

TABLE III. The average yarns contact angle (θ).

Fabric Code	θ (Degree)
C1	159.18
C2	158.93
C3	164.86
CP1	159.189
CP2	159.643
CP3	165.403
CN1	159.58
CN2	159.96
CN3	165.652

It should be noted that, while the pullout force increases to reach to its maximum value, the static friction coefficient (μ_s) should be used in Eq. (7), and afterwards, the dynamic friction coefficient (μ_k) should be used.

The experimental and theoretical values of stored energy in the fabrics and the percentage of the difference between them are shown in *Table IV*.

TABLE IV. Experimental and theoretical stored energy in the fabrics.

Fabric Code	Experimental stored energy (N.mm)	Theoretical stored energy (N.mm)	Difference (%)
C1	191.96	193.98	1.037
C2	137.07	132.99	2.97
C3	101.43	96.77	4.59
CP1	263.11	261.19	0.73
CP2	194.28	193.41	0.44
CP3	162.27	169.36	4.19
CN1	225.30	222.15	1.39
CN2	181.72	177.62	2.25
CN3	150.19	145.66	3.01

According to *Table IV* the maximum difference between experimental and theoretical values is less than 5%.Therefore, it can be concluded that the presented theoretical model shows a reasonable prediction of the stored energy in these fabrics. The difference between experimental and theoretical results could be attributed to some experimental errors, and also loose structure of fabrics with long loop length, which causes misplacing of the fabric in the U form frame.

Effect of Fabric Material on the Stored Energy in the Fabric

The effect of fabric material on the stored energy in the fabric is shown in *Figure 10*. It is observed that, the cotton/polyester fabric has the maximum stored energy, due to its higher yarn to yarn friction coefficient. Cotton/nylon and cotton fabrics are in the next stages respectively. It is obvious that, increase in friction coefficient will increase the frictional force and the stored energy in the fabric consequently.

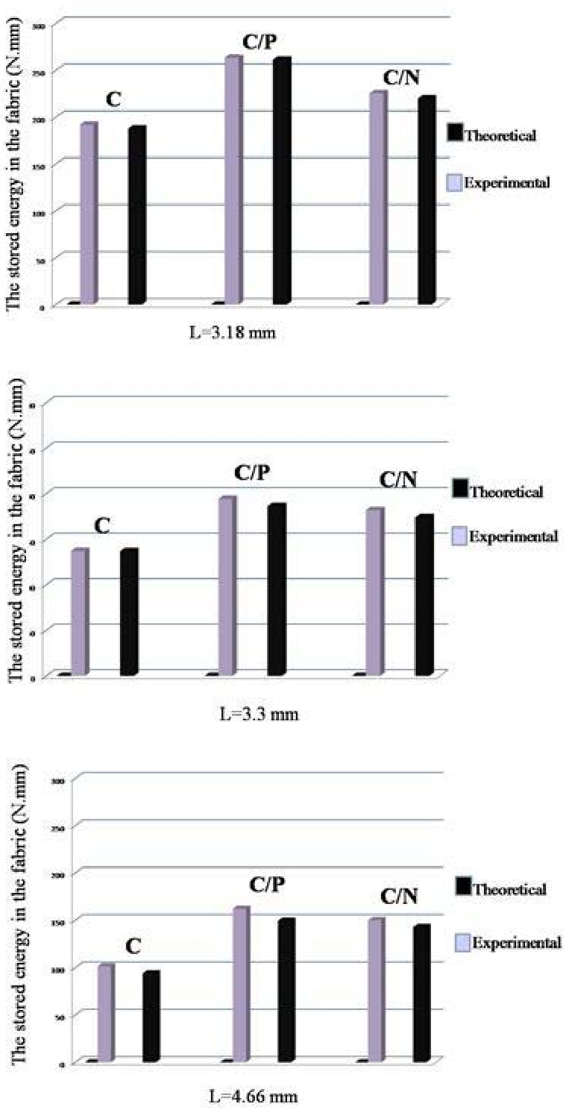

FIGURE 10. Effect of fabric type on the stored energy in the fabric.

Effect of Fabric's Loop Length on the Stored Energy in the Fabric

The effect of fabric loop length on the stored energy in the fabric is shown in *Figure 11*. This figure reveals that, for all fabrics, the increase in fabric's loop length leads to decrease in the fabric's stored energy, which is due to loose fabric structure which causes less friction between the loops.

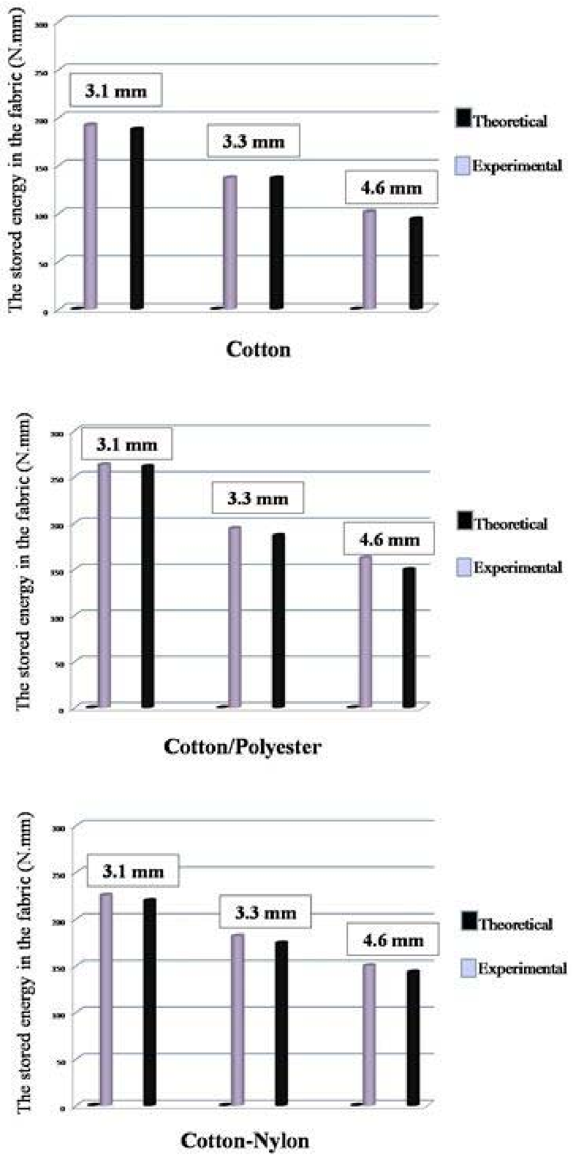

FIGURE 11. Effect of fabric's loop length on the stored energy in the fabric.

CONCLUSION

In this study, a theoretical yarn pullout model is presented to estimate the stored energy of plain-knitted fabrics. This model is based on the fabric dimensional properties i.e., stitch length, and contact angle of yarns, using force balance analysis. The percentage of difference between experimental and theoretical stored energy in the fabrics indicated that the presented theoretical model shows a reasonable prediction of the stored energy in these fabrics.

The effect of fabric material on the stored energy in the fabrics was investigated. The cotton/polyester fabric had the maximum stored energy, due to its higher yarn to yarn friction coefficient. Cotton/nylon and cotton fabrics were in the next steps respectively. It is obvious that, increasing in friction coefficient will causes increase the frictional force and the stored energy in the fabric. Investigation of the effect of fabric's loop length on the stored energy in the fabrics revealed that, for all fabrics, the increase of fabric's loop length leads to decrease in the fabric's stored energy.

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