Study on the Comfort of Knitted Elastic Fabrics based on Compressive Deformation Behavior

Ehsan Pazireh, Ali Akbar Gharehaghaji, PhD, Ezzatollah Haghighat

Amirkabir University of Technology, Tehran, IRAN

Correspondence to:
Ali Akbar Gharehaghaji email: aghaji@aut.ac.ir

ABSTRACT
Comfort is one of the most important factors influencing the performance of apparel such as knitted elastic clothing, woven elastic shirts and elastic velvet fabrics. The compressive behavior of knitted elastic fabric affects the excellence in comfort. This study aimed to investigate the comfort of knitted elastic fabric based on compressive load. For this purpose, fabrics were produced with three different stitch densities (loop sizes), and compressive load tests were applied at three various penetration depths. According to these parameters, 9 fabric samples were prepared. Each sample was tested 30 times; therefore, the total number of examined cases was 270. The compressive load was measured using special designed tools, which were installed on the Instron tensile tester. The effects of penetration depth and loop size on compressive load were evaluated by using the CCD statistical model with four repeats of each experiment. The results indicate that the loop size and penetration depth have significant influence on the compressive load, which is modeled by a third order equation with R^2 of 0.999 between applied model and experimental data. Consequently, the comfort could be predicted in terms of loop size and penetration depth. Utilizing this method can help apparel manufactures produce knitted elastic clothing with high comfort, according to the end use of garment.

Keywords: Comfort, Knitted elastic fabrics, Loop size, Compressive load, Penetration depth

INTRODUCTION
The development of the garment industry and social life, positively influence the efficiency of clothes. Consumers are keen to wear clothes, which have the best comfort and performance [1]. Therefore, the selection of clothes needs something more than the common sense of seeing, smelling, or touching, which is called comfort in textile science [2]. In other words, conventional concepts such as warmness, coolness, roughness, breathability, and movement facility are briefed in convenience factor [3]. Clothing can enhance the interactions between the body and the environment, which in turn causes physical, physiological, and psychological comfort [4, 5]. Thus, the main goal of apparel industry is to obtain ultimate comfort in clothing.

Knitted fabrics are widely used for apparel and fashion garments such as elastic jeans or elastic velvet clothes, household clothing, medical, and industrial wear [3, 6, 7].

To obtain better compressive properties of knitted fabrics, Lycra and spandex yarns are blended with cotton, wool, polyester, and other fibers. Such blends yield appropriate elastic properties in yarns and fabrics. They also bring about a feeling of comfort, due to easy movement of the body in sewn clothes. As a result, they provide more convenience for consumers [8- 9].

Pressure applied by the fabric on the body depends on three factors, namely the shape of the body that is supposed to be covered by fabric, fiber type, and fabric design [10]. To achieve the desired properties of garment, predicting the amount of pressure is necessary [11]. Curvature and protuberance increase bring about more pressure on the clothes. This indicates that putting load on a specific part of body with more eminence (such as the leg), is more comfortable than other parts which have less eminence (such as the wrist) [11, 12].

The elasticity of knitted clothes is reduced through wearing. Therefore, design of this type of fabric must result in the right size [13-16]. Moreover, design of these clothes should not prevent the consumer from putting them on or off easily. Thus, the pressure exerted from fabric to body must be constant over the life time of the garment [17-21]. In the other words, design of these clothes must provide an adequate level of convenience [22-25].

There are two methods for measuring the pressure. In the first method, a pressure gauge is used to measure the interfacial pressure between the two levels (the pressure that the fabric puts on the body). In the second method, an Instron tensile tester is used to measure compressive state [11, 13, 14].

In this study, to evaluate the comfort of knitted elastic fabric, the effects of fabric loop size and penetration depth on the compressive load were investigated. The results of fabric compression tests were assessed using the CCD (central composite design) response model.

MATERIALS AND METHODS

In order to compare the effect of the two independent variables of loop size and penetration depth on the compressive load as response variable, three types of fabrics were knitted with Lycra/cotton core spun yarn. The Lycra was a four filament and specific density of the cotton covered Lycra yarn was 30 Tex. The mean breaking load and elongation of prepared yarns were 2.2 (*N*) and 19.6 (*mm*).

Loop lengths of 4.6, 6.1, and 7.3 (*mm*); and stitch densities of 276, 210, and 140 (per 100 cm^2) were applied. Tests were carried out for assessment of bending rigidity (which indicates the flexibility and fabric resistance versus exerted forces), air permeability (the variable related to the fabric breathability is important to be determined in fabric comfort), fabric thickness and stitch density (which are the general variables of any fabric) according to the relevant standards (ASTM D2256, ASTM D1388, BS5636, ASTM D1777 and ASTM D3775, respectively). The results are shown in *Table I*

TABLE I. Specifications of knitted fabric samples.

Fabric Code	Fabric Structure	Stitch Density (per 100 cm^2)	Loop Size (cm)	Weight (g/m^2)	Thickness (mm)	Bending Rigidity(mg.cm)		Air Permeability (ml/s.cm2)
						Warp Direction	Diagonal Direction	
A	Plain	276	0.46	175.1	0.96	1296.5	960.3	39.6
B		210	0.61	152.3	1.14	709.2	410.4	57.4
C		140	0.73	130	1.28	387.3	203.1	69.2

Compression Characteristics

In order to measure compressive load, a special device were designed and constructed, in which the two jaws of Instron tensile tester were used (*Figure 1*). The diameters of the lower jaw (5) and upper jaw (1) were 17.5 and 10 (*cm*), respectively. The fabric sample (3) with diameter of 3 (*cm*) was placed on the holder jaw (4), which was located on the lower jaw. The jaw cover prevented it from slipping, and circular surface enabled uniform force distribution in all directions. Indenter arm (2) was a spherical surface with a diameter of 5 (*mm*). Penetration depth of indenter was set to be 13, 25 and 30 (*mm*). Thirty tests were done for each fabric in each penetration level.

Modeling of Compressive Behavior

To evaluate the effect of loop size and penetration depth on the compressive load, the obtained data of compression tests were analyzed, by using the CCD (central composite design) response model. For this purpose, the *Design Expert* software version 8 was applied.

The mathematical equation governs the independent variables (loop size and penetration depth), and response variable (compressive load) which have been reported. The degree of adjustment between the achieved equation and the experimental results were investigated according to relevant statistical data analysis of variance table (ANOVA).

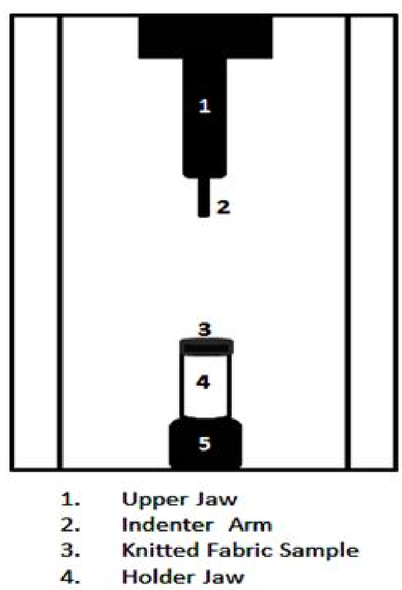

FIGURE 1. Experimental set up for measuring the compressive force by Instron Tensile Tester.

Average values of experimental results for fabric samples are reported in *Table II*. The design of the experiment in this stage was performed by using the CCD statistical model with four repeats of each experiment and the center point.

TABLE II. Results of measuring the compressive strength for samples A, B and C.

			Penetration Depth (mm)		
			13	**25**	**30**
Compressive Load (N)	A	Average	**0.99**	**2.97**	**14.55**
		CV%	**6.06**	**9.09**	**9.97**
	B	Average	**0.43**	**1.34**	**5.68**
		CV%	**11.63**	**5.22**	**6.87**
	C	Average	**0.29**	**0.95**	**2.76**
		CV%	**13.8**	**7.37**	**14.49**

TABLE III. Analysis of Variances (ANOVA) to evaluate the effects of loop size and penetration depth on the compressive load.

Source	Sum of Squares	df	Mean square	F Value	p-value Prob > F
Model	8.64	7	1.23	4037.35	< 0.0001
A-Loop Size	0.40	1	0.40	1305.62	< 0.0001
B-Penetration Depth	2.42	1	2.42	7935.43	< 0.0001
AB	0.26	1	0.26	864.61	< 0.0001
A^2	0.017	1	0.017	55.68	< 0.0001
B^2	0.12	1	0.12	377.32	< 0.0001
A^2B	0.014	1	0.014	45.95	< 0.0001
AB^2	0.030	1	0.030	99.23	< 0.0001
Residual	8.556E-003	28	3.056E-004		
Lack of Fit	9.384E-004	1	9.384E-004	3.33	0.0793
Pure Error	7.618E-003	27	2.821E-004		

By checking the common simulations with achieved results (according to some predefined models), it can be concluded that the effect of loop size and penetration depth on the compressive load follows a third order equation. The final results of the ANOVA table were obtained by using software Transform in the Inverse Sqrt mode to reduce the F parameter of LOF (Lack of Fit) model. Analysis of variance (ANOVA) results for this stage are presented in *Table III*.

RESULTS AND DISCUSSION

According to the statistical tests (*Table IV*), it can be seen that the *R-Sq.* (adj.) of the model is 0.999. This indicates an acceptable correlation between actual and predicted values of the response variable. Also, the value of the predicted *R-Sq.* is 0.998. In comparison with the value of *R-Sq.* (adj.), this represents an application of logical model to this case (*Figure 2*). The values of *R-Sq*, given in Table IV, confirm the applicability of the model to analyze the experimental data.

R-Squared	0.9990
Adj. R-Squared	0.9988
Pred. R-Squared	0.9983
Adeq. Precision	193.6690

TABLE IV. The relationship between applied model and experimental data values of compressive load.

Accuracy of the model is verified according to the obtained value (Adeq. Precision=193.67). Moreover, the *P-value* and *F* parameter (LOF) of the model are 0.079 and 3.33, respectively (*Table III*). This indicates that the commutated model is appropriate and the difference between applied model and experimental data is not significant (p-value = 0.0793>0.05).

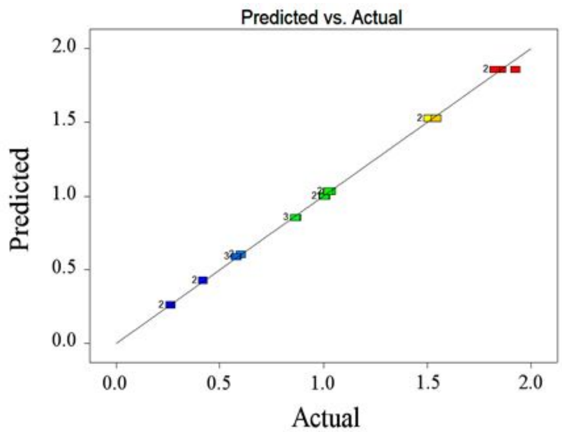

FIGURE 2. Response predicted values expression versus actual values.

Therefore, the final equation to estimate the quantitative effects (interaction and independent effect) of loop size and penetration depth on the compressive load can be defined by using the nonlinear multi-regression as follows:

$$1/(Load)^{0.5} = 0.856 + 0.223 \times L - 0.551 \times P - 0.129 \times L \times P - 0.046 \times L^2 + 0.120 \times P^2 + 0.051 \times L^2 \times P + 0.075 \times L \times P^2 \quad (1)$$

Where
L: loop size, and P: penetration depth

Individual (main) effect of loop size and penetration depth on the compressive load is presented in *Figure 3*. It can be seen that the effect of the loop size and penetration depth on the inverse square of compressive load is positive and negative, respectively. According to the *Figure 3B*, the intensity of this effect is higher for penetration depth. These effects are expressed in the form of positive and negative coefficients, in the final equation.

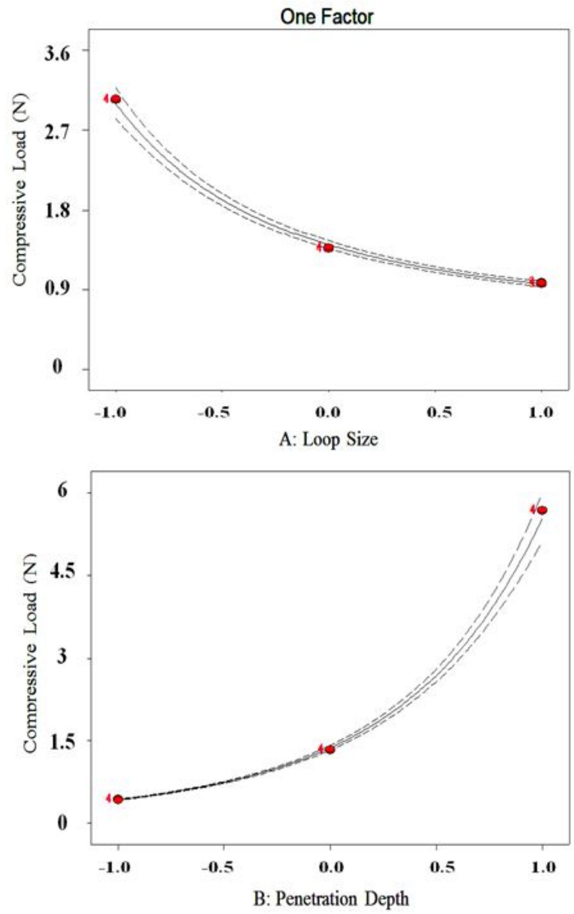

FIGURE 3. Effects of loop size and penetration depth on the compressive load (A: loop size, B: penetration depth).

Regarding *Figure 3*, when the fabric undergoing compression, at first, the deformation is caused by the movement of loops in the fabric structure, which is mainly an elastic and reversible deformation. Then, by increasing of the force, the fiber movement in the yarn inner structure is increased. This is considered as plastic deformation which is time-dependent. In fact, by reducing the loop size, available space for fiber motion will be limited. In the other word, in a fabric with the smaller loop size, the yarn has a lower elongation by exerting the same force. In fabrics with open structure, there is more space for the movement of the loops. Thus, in comparison to a fabric with dense structure, it is more elastic.

In *Figure 3*, the effect of compressive load on the penetration depth is presented. At lower density, the distribution of compressive force on the fabric surface is not uniform. However, with more compression, the yarns are moved to the new situations which are in contact with their adjacent yarns. So, the degree of compressive force is increased with more inclination.

Figure 4 presents the interaction of the two independent variables on compressive load. It shows that the difference between the compressive load of fabric samples is not statistically significant, especially, at low compressive stresses about 2 (*N*). So, it can be concluded at this level of compressive load, only the displacement of loops in fabric structure occurs. At higher compressive load, a significant difference is observed between the forces acting on the fabric. This is attributed to the stitch density reduction which leads to decrease in the number of yarn loops within the fabric. This causes an increase in the compressive load applied on each yarn loop.

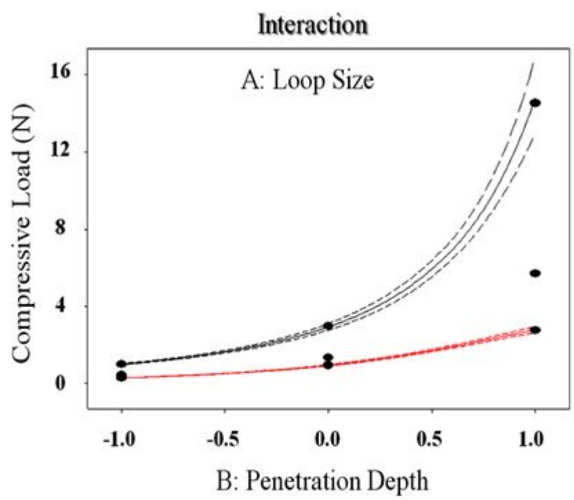

FIGURE 4. The interaction of loop size and penetration depth on the compressive load.

Three dimensional and layer diagrams in *Figure 5* show the interaction of loop size and penetration depth on the compressive Load. As can be seen, the highest value of load compression is obtained at the highest value of penetration depth and the lowest value of loop size.

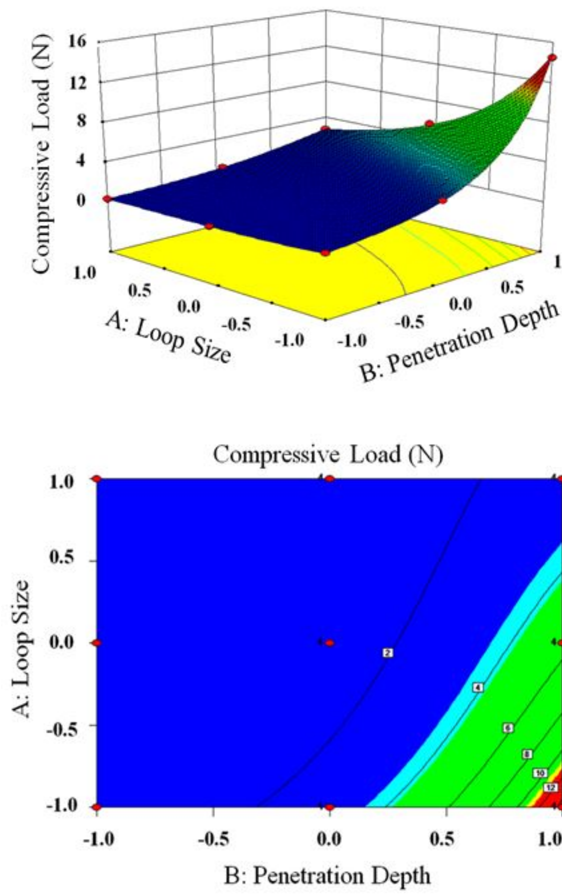

FIGURE 5. Effects of loop size and penetration depth on the compressive load (three dimensional and layer graphs).

According to the final equation, the findings show that increasing of the number of loops causes an increasing in the knitted fabric elasticity. On the other hand, increasing the stitch density can lead to limitation in yarn free movements. Thus, when fabric is compressed with force about 2 (*N*), this force is spent for opening the yarn curls and waves. Increasing of the force will be associated with elongation of yarn. Augmenting of the yarns elongation rate due to raising the penetration depth causes an increasing in the value the compressive load. This increase can be calculated by Eq. (1).

As previously mentioned, it is possible to predict the comfort of knitted elastic fabrics based on compressive load. When the compressive load increases, comfort decreases; because higher load needs to displace the yarn in the fabric structure. The results show that by increasing the loop size, the compressive load reduces. Moreover, compressive load increases by penetration depth. So the physical sense becomes poor.

CONCLUSION

In this research, the comfort of knitted elastic fabrics on the basis of compressive load was investigated. In order to analyze the effect of loop size and penetration depth (as independent variables) on the compressive load (as dependent variable), the *Central Composite Design* response was used. The compressive load was measured by utilizing special tools mounted on the Instron tensile tester. By using the nonlinear multi-regression method, compressive load could be predicted based on penetration depth and loop size. The findings show that there is a good correlation between the experimental and predicted values (R^2 = 0.999). By predicting the compressive load (developed model), it is possible to forecast the comfort (especially physical comfort) of knitted elastic fabric based on end use of product. Based on the statistical analysis of the results, it can be found that the stitch density (loop size) has a significant effect on the compressive load. With decreasing of loop size the compressive load increases. By reducing of loop size (increasing of stitch density), the free space between loops in fabric structure decreases, so loops move difficultly. Therefore, in fabrics with denser structure, because of less free space in fabric construction, the compressive load is higher than looser fabric. Moreover, the compressive load is influenced by penetration depth. With decreasing penetration depth, the compressive load decreases. Generally, the comfort of fabric depends on the end use of apparel. For instance, in medical applications the compressive load should be adjusted according to type of disease and remedy, which it can be different from one type to others. In some conditions, a fabric with high compressive load (high bending rigidity) is needed; however, the usage of this fabric, because of small extensibility, in other clothing applications is not proper.

REFERENCES

[1] Bertaux, E.; Derler, S.; Rossi, R.; Zeng, X.; Koehl, L and Ventenat, V.; "Textile, Physiological, and Sensorial Parameters in Sock Comfort", Textile Research Journal, Vol.80, 2010, pp. 1803-1810.

[2] Y. Li and X-Q. Dai; "Biomechanical engineering of textiles and clothing", Woodhead Publishing Limited, Hong Kong, 2006, pp. 145-159.

[3] Hollies, N. R. and Goldman, R. F.; "Clothing Comfort: Interaction of Thermal Ventilation, Construction, and Assessment Factors", Ann Arbor Science, Ann Arbor, MI, 1977.

[4] Wang, G.; Zhang, W.; Postle, R and Phillips. D.; "Evaluating Wool Shirt Comfort with Wear Trials and the Forearm Test", Textile Research Journal, Vol.73, 2003, pp. 113-119.

[5] Oglakcioglu, N.; Celik, P.; Ute, T.B.; Marmarali, A and Kadoglu, H.; "Thermal Comfort Properties of Angora Rabbit/Cotton Fiber Blended Knitted Fabrics", Textile Research Journal, Vol.79, 2009, pp. 888-894.

[6] Yoo, S and Barker, R.L.; "Comfort Properties of Heat Resistant Protective Workwear in Varying Conditions of Physical Activity and Environment. Part II: Perceived Comfort Response to Garments and its Relationship to Fabric Properties", Textile Research Journal, Vol.75, 2005, pp. 531-541.

[7] Scheurell, DM.; Spivak, SM.; Hollies, NRS.; "Dynamic surface wetness of fabrics in relation to clothing comfort", Textile Research Journal, Vol.55, 1985, pp. 394-399.

[8] Cil, MG.; Nergis, UB.; Candan, C.; "An experimental study of some comfort-related properties of cotton-acrylic knitted fabrics", Textile Research Journal, Vol.79, 2009, pp. 917-923.

[9] Verdu, P.; Rego, Jose M; Nieto, J.; Blanes, M.; "Comfort analysis of woven cotton/polyester fabrics modified with a new elastic fiber. Part1: Preliminary analysis of comfort and mechanical properties", Textile Research Journal, Vol.79, 2009, pp. 13-23.

[10] Tsujisaka, T.; Azuma, Y.; Matsumoto, Y.-i.; Morooka, H.; "Comfort Pressure of the Top Part of Men's Socks", Textile Research Journal, Vol.74, 2004; Part 7, pp. 598-602.

[11] Aghajani, M.; Amani Tehran, M.; Asgharian Jeddi A.; "Precise Measurement of Tension on Curvature Elastic Shells", Journal of Engineered Fibers and Fabrics, Volume 8, 2013, pp. 82-87.

[12] Lau, L.; Fan, J.; Siu, T.; Siu, LYC; "Comfort sensations of polo shirts with and without wrinkle-free treatment", Textile Research Journal, Vol.72, 2002, pp. 949-953.

[13] Tae Jin, Kang; Chung, Hee Park.; Youngmin, Jun and Kyungho, Jung; "Development of a Tool to Evaluate the Comfort of a Baseball Cap from Objective Pressure Measurement: (I) Holding Power and Pressure Distribution", Textile Research Journal, Vol.77, 2007, pp. 653-660.
[14] You, F.; Wang, J. M.; Luo, X. N.; Li, Y and Zhang, X.; "Garment's Pressure Sensation (1): Subjective Assessment and Predictability for Sensation", International journal of Clothing Science Technology, Vol. 14, 2002, pp. 317-327.
[15] Cardello, V and Winterhalter, C.; "Prediction the Handle and Comfort of Military Clothing Fabric from Sensory and Instrumental Data", Textile Research Journal, Vol. 73, 2003, pp. 221-237.
[16] B.K. Behera.; "Comfort and Handle Behavior of Linen-Blended Fabrics", Autex Research Journal, Vol. 7, 2007, pp. 33-47.
[17] Murthyguru, I.; "Novel approach to Study Compression Properties in Textile", Autex Research Journal, Vol. 5, 2005.
[18] Wensheng, H.; "Online characterization of fabric compression behavior", PhD Thesis, Fiber and Polymer, North Crolina State University, 1999.
[19] Yip, J.; S, Ng; "study of three-dimensional spacer fabrics: Physical and mechanical properties ", Journal of materials processing technology, 2008, pp359-364.
[20] Oden, J.T.; "Mechanics of Elastic Structures", McGraw-Hill, Inc., USA, 1967, pp130-136.
[21] Debnath, S and Madhusoothanan, M.; "Compression Properties of Polyester Needle punched Fabric", Journal of Engineered Fibers and Fabrics, Vol. 4, 2009, pp.14-19.
[22] Wang, L.; Felder, M.; Jackie, Y. Cai.; "Study of Properties of Medical Compression Fabrics", Journal of Fiber Bioengineering & Informatics, Vol.4, 2011, pp.15-22.
[23] Ghosh, S.; Mukhopadhyay, A.; Sikka, M.; Nagla, KS; "Pressure mapping and performance of the compression bandage/garment for venous leg ulcer treatment", Journal of Tissue Viability, Vol. 17, 2008, pp.82-94.
[24] Shishoo, R.;"Textiles in sport", Woodhead Publishing Limited in association with The Textile Institute, 2005.
[25] Wong, A. S. W.; Li, Y.; Yeung, P. K. W.; "Predicting Clothing Sensory Comfort with Artificial Intelligence Hybrid Models", Textile Research Journal, Vol.74, 2004, pp. 13-19.

AUTHORS' ADDRESSES

Ehsan Pazireh
Ali Akbar Gharehaghaji, PhD
Ezzatollah Haghighat
Amirkabir University of Technology
Hafez Avenue
Tehran. 1591634311
IRAN