(REFEREED RESEARCH)

INVESTIGATION OF THE MECHANICAL TESTING CONDITIONS ON SENSING PROPERTIES OF TEXTILE-BASED STRAIN SENSOR

MEKANİK TEST KOŞULLARININ TEKSTİL BAZLI UZAMA SENSÖRLERİNİN ALGILAMA ÖZELLİKLERİNE ETKİSİNİN İNCELENMESİ ÜZERİNE BİR ARAŞTIRMA

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Received: 23.05.2016 Accepted: 31.08. 2016

ABSTRACT

The aim of this research study is to investigate the effect of different mechanical test conditions on the sensing properties of proposed knitted strain sensors. In order to fulfill this aim, initially, the effect of quasi-static testing on the sensing properties of sensors is discussed. Thereafter, effect of the tensile testing machine cross head speed on sensor characteristics is investigated. A single design of proposed knitted strain-sensing fabric was devised using computerised flat-bed knitting technology, comprising silver coated nylon conductive yarn with 2 Ω/cm linear resistance and insulating core-spun Lycra yarns with different yarn fineness. It was observed that that sensors produced with the yarn low extension capability showed less imprecision during quasi-static tests and alteration on machine crosshead speed also affected some sensor properties such as hysteresis and linearity but no affect found on gauge factor values. Proposed knitted strain sensing structures can be used for measuring the physiological parameters of the human body, i.e., respiration rate or body articulation.

Keywords: Knitted sensor; strain sensor; knitting; test conditions; silver yarn

ÖZET

Bu çalışma farklı mekanik test koşullarının örme yapılı uzama sensörlerinin algılama özelliklerine etkisini incelemektedir. Bu amaç doğrultusunda öncelikle yarı statik test koşullarının sensörlerin algılama özelliklerine etkisi tartışılmıştır. Daha sonra ise çekme makinesinin üzerindeki hareketli çenenin kumaşa uyguladığı farklı çekme hızlarının sensör karakteristiklerine etkisi incelenmiştir. Örme yapılı sensörler 2 ohm/cm elektrik direnine sahip gümüş kaplı naylon iplikleri ve farklı kalınlığa sahip elastomerik iplikler kullanılarak düz örme makinesinde üretilmiştir. Yarı statik test sonuçlarına göre; göreceli olarak daha az uzama kapasitesine sahip elastomerik ipliklerle üretilen sensörler daha az elektriksel ölçüm hatası vermiştir. Ayrıca, farklı çekme hızlarının sensörlerin histeresiz ve doğrusallık değerlerine etkisi gözlemlenirken, hassasiyet değerlerine etkisi gözlemlenmemiştir. Bu çalışmada incelenen sensörler insan fizyolojik özelliklerinin ölçülmesinde kullanılabilir.

Anahtar Kelimeler: Örme sensörler, gümüş kaplı iplik, uzama sensörleri, mekanik test ,elastomerik iplik

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1. INTRODUCTION

Over the last decade, a growing number of research related to electronic textile systems has been conducted [1-5]. These systems are intended to be used in the areas of health monitoring, sports performance training, military, and entertainment. Electro-textile systems consist of a number of different components that fulfill different tasks within a system. The types of these components may vary depending on the application area of the structure. However, most electro-textile structures require specific categories of components in order to perform their task reliably: sensors/electrodes, power supply, a communication network within the structure, a data processor and an actuator are the basic elements of the system [6]. Among these components, sensors are the key input interfaces for electro-textile systems. In general, they can be described as devices that detect a change in physical stimulus and turn it into a signal, usually electrical, that can be measured or recorded [7]. Since textile-based sensing structures are more flexible and lightweight due to the inherent properties of textile structures in comparison to rigid electronic instruments; they increase the wearer`s comfort during long term usage and they fit closely against the human body [8]. Thus, special attention has been paid for the development of such systems. The working principle of many textile-based sensing technologies in the area of electronic textiles can be classified according to the operation principle in the following classes: inductive [9], capacitive [10], resistive [11] and piezoelectric [12]. Various successful prototypes have been developed through these technologies for measuring human physiological parameters such as skin temperature [13], heart rate [14], breathing rate [15], ECG [16] as well as monitoring human body movements [17]. Among these measurements, monitoring joint articulation and respiration rate are greatly attracted researchers; since respiration pattern gives valuable information about the general health condition of the wearer and monitoring joint articulation may find application includes but not limited to sports training, entertainment, and healthcare. Quite often resistive strain sensing technology is utilized for joint and respiration monitoring. Resistive strain sensors have inherent ability to change their electrical resistance in proportion to the applied strain magnitude [18]. Previous studies have demonstrated that resistive sensing structures can be developed using conventional textile production methods such as knitting [19-21], weaving [22], coating [23] and printing [24]. In this study, weft knitted strain sensors based on resistive sensing technology has been chosen for investigation due to following reasons; since proposed application area of these sensors is monitoring human body movement and respiration, they should be in close contact with human body. Also, resistive technology provides relatively easy measurement circuitry compared with other technologies. In connection to this study few more articles have been published; the design and characterization of the knitted strain sensor; and the application of knitted sensor in the area of respiration monitoring have been demonstrated in earlier articles [8,11].

Within the domain of medical/smart textiles, the development and the characterization of the textile strain sensors has gained importance in last decade; however little investigation has been done to understand the effect of mechanical test conditions on sensing mechanism of strain sensors. Therefore primary aim of this article is to assess the sensing performance of the knitted strain sensors under different mechanical test conditions. For this purpose, 2 different types of knitted sensors were manufactured. Knitted sensors which differentiate from each other in terms of compactness level. Thereafter, effect of quasi-static tests and variable crosshead speeds on sensor performance were investigated.

2. MATERIALS AND METHODS

2.1. Production of knitted strain sensors

Knitted strain-sensing fabrics were devised using silver coated nylon conductive yarn with 2 Ω/cm linear resistance and insulating core-spun Lycra yarn (see Figure 1). Silver plated nylon yarn was chosen due to its continous conductivity along the fiber surface.Two different variations of the basic knitted sensing fabric were created using 800 dtex, and 570 dtex Lycra elastomeric yarns respectively. The elastomeric core of each Lycra yarn was wrapped with a double covering of continuous filament nylon. The two variants of the sensing structure were manufactured on a Shima Seiki SES 122-S ten gauge computerised flat-bed knitting machine while their structures were initially designed using Knitpaint software before manufacturing on knitting machine. Compactness is an important fabric property which affects fabric properties including dimensional stability, strength, drape, handle and shrinkage. Normally, structures with a high tightness factor means higher wale and course densitites and reduced wale and course spacing resulting in a higher contact pressure between adjacent courses and wales. Table 1 shows manufacturing parameters of the proposed sensors. Thus, order of the compactness of the knitted structures is type 2> type 1 based upon the lycra yarn extension level.

Table 1. Production parameters of sensing structures

Sample type	Core lycra Linear Yarn Density (dtex)	Elastomeric Yarn Input Tension (cN)	Number of Conductive Wales	Number of Conductive Courses
Type 1	800	8	36	6
Type 2	570	8	36	6

Elastomeric Yarn Type	Applied Force (cN)	Extension (%)
800 dtex core Lycra with double PA 6.6 covering	8 cN	175.2
570 dtex core Lycra with double PA 6.6 covering	8 cN	260.97

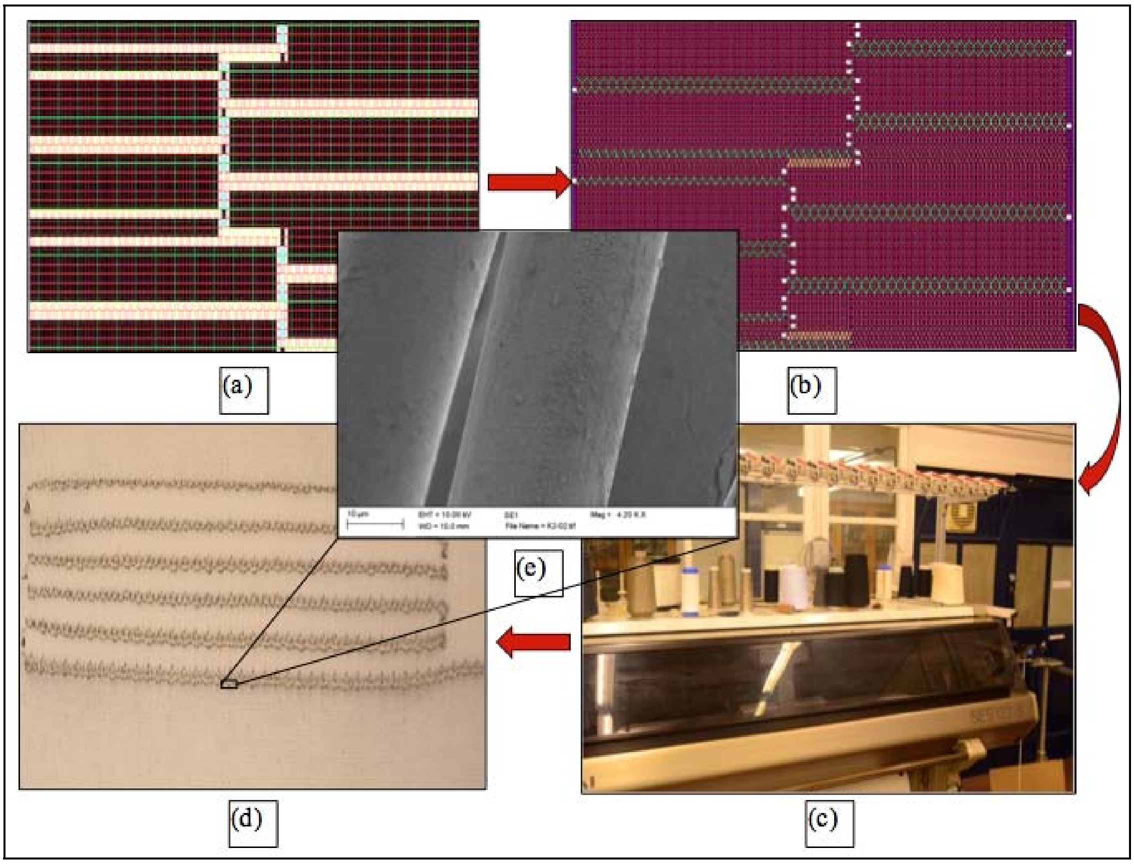

Figure 1. Production of knitted sensors . **(a)** CAD of knitted structure **(b)** yarn path notation **(c)** Shima Seiki computerized knitting machine **(d)** actual image of knitted sensor **(e)** SEM image of silver plated nylon yarn

2.2. Working priciple of knitted strain sensors

The sensing mechanism of the sensor relies on the design of the silver plated yarn in the fabric structure that provides the sensor to change its electrical resistance in response to applied load. The rearrangement of the contact points between adjacent loops of the conducting yarn is the main controlling factor for the behaviour of the sensing mechanism. To illustrate the situation, Figure 2 shows a schematic diagram of one conductive course within the structure. As the sensor stretches widthwise, its wale density reduced and the contact points are separated which resulted in the increased electrical resistance values.

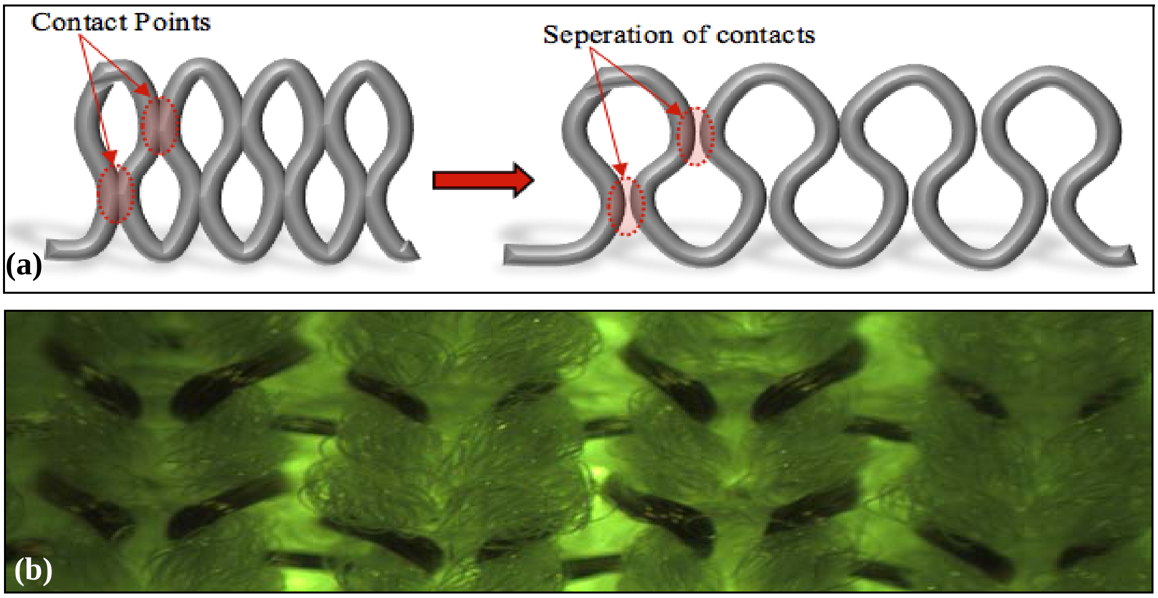

Figure 2. Working mechanism of sensor **(a)** scehematic diagram of single conductive course and the loop contact scheme **(b)** Magnified image of knitted sensor shows seperation of conductive loops at 40 % strain

According to the Holm's contact theory;

$$Rc = \frac{\rho}{2}\sqrt{\frac{\pi H}{np}} \quad (1)$$

where:

Rc= contact resistance;

ρ = electrical resistivity;

H = material hardness;

n = number of contact points;

p = contact pressure.

From Equation (1), it is understood that the level of loop contact areas and the contact pressure depends upon applied strain. Thus, contact resistance within the conductive path reduces when contact pressure and contact areas increases. In this sensor design, the contact pressure and the number of contact areas between the conductive loops were maximum prior to applied load. Thereafter, contact pressure and, contact area between conductive loops decreases in response to applied strain due to seperation of conductive path and this results in increasing of electrical resistance values due to the increase of electrical contact resistance.

In this case,sensitivity of the sensors is defined as gauge factor (GF) and is calculated as shown (2).

$$GF= \frac{\frac{\Delta R}{R}}{\varepsilon} \quad (2)$$

where:

ΔR = the change in the resistance;

R = the initial resistance before extension;

ε = the strain value.

2.3. Test Methodology

2.3.1. Test Rig

The electromechanical characterisation of the sensor was determined using a Zwick-Roell Z 2.5 (Zwick GmbH & Co., Ulm, Germany) tensile tester in combination with a Wheatstone bridge circuit while data were recorded in real time using TestExpert (TestXpert®, Zwick GmbH & Co, Ulm, Germany) software. The tensile testing machine provides a regulated voltage input for the Wheatstone bridge. Resistance values were obtained from the conversion of voltage values to resistance values by using standard Wheatstone bridge analysis.

2.3.2. Effect of Quasi-static tests on sensor characteristics

In order to perform quasi-static tests, each sensor was elongated up to the 40 % strain level at a 120mm cross-head speed. The extension level of 40% was chosen to mirror typical human body extensions, as the proposed sensor can be used for monitoring human body movements. Sensors were tested by holding them for 30 sec at 40 % and 0 % strain levels. This process of changing strain level was repeated six times.

2.3.3. Effect of crosshead speed on sensor characteristics

In order to see the effect of crosshead speed on sensor characteristics, type 2 sensors were utilized. The tests were performed at various crosshead speed settings, i.e., 60mm/min, 120mm/min, 240mm/ min and 480mm/min.

3. RESULTS AND DISCUSSION

3.1. Quasi-static tests

In Figure 3 the relaxation behaviour of the sensors during the cyclic quasi-static tests is shown. The dwell times at maximum and minimum strains are 30 seconds in each cycle as explained in 2.3.2 and it is also important to measure absolute electrical resistance values during the dwell periods. Table 2 and table 2 statistically analyzes the absolute electrical resistance values and the relative electrical resistance values respectively during the quasi-static tests.

As seen from Table 2, when the compactness of the fabric increased (as presented in Table 1),the level of electrical resistance relaxation increased. This originates from the intrinsic behavior of the elastomeric fabric structure which the electrical resistance behavior of knitted sensors. However, when the relative change in resistance of sensors (as shown in Table 3) is taken into account, relaxation values differ from Table 2, so Table 3 provides these new values. The reason for this difference is that values in Table 2 were calculated according to sensors` absolute electrical resistance values which are the whole resistance values of the sensors. However, the values in Table 3 were calculated according to the relative change in resistance.

3.2. Crosshead speed tests

In order to see the effect of crosshead speed on sensor characteristics, type 2 sensors were utilized. Tests were performed at the set crosshead speed of as 60mm/min, 120mm/min, 240mm/min and 480mm/min. Thereafter, change in hysteresis values, linearity of the sensors and gauge factors were investigated according to the applied crosshead speed. Although considerable research has been carried out in the creation of wearable strain sensors, however only a few systems have been commercialized so far. Non-linearity and the hysteresis in the response to applied strain could be considered as the prime reason behind the lack of commercialization.

Hysteresis can be explained as a difference between two outputs values, which correspond to the same, input (past and present) stimulus because of the change in the internal state of system. Table 4 presents hysteresis values of the sensor at the various applied crosshead speed. The hysteresis values were calculated according to the maximum difference between strain values in response to same electrical resistance value.

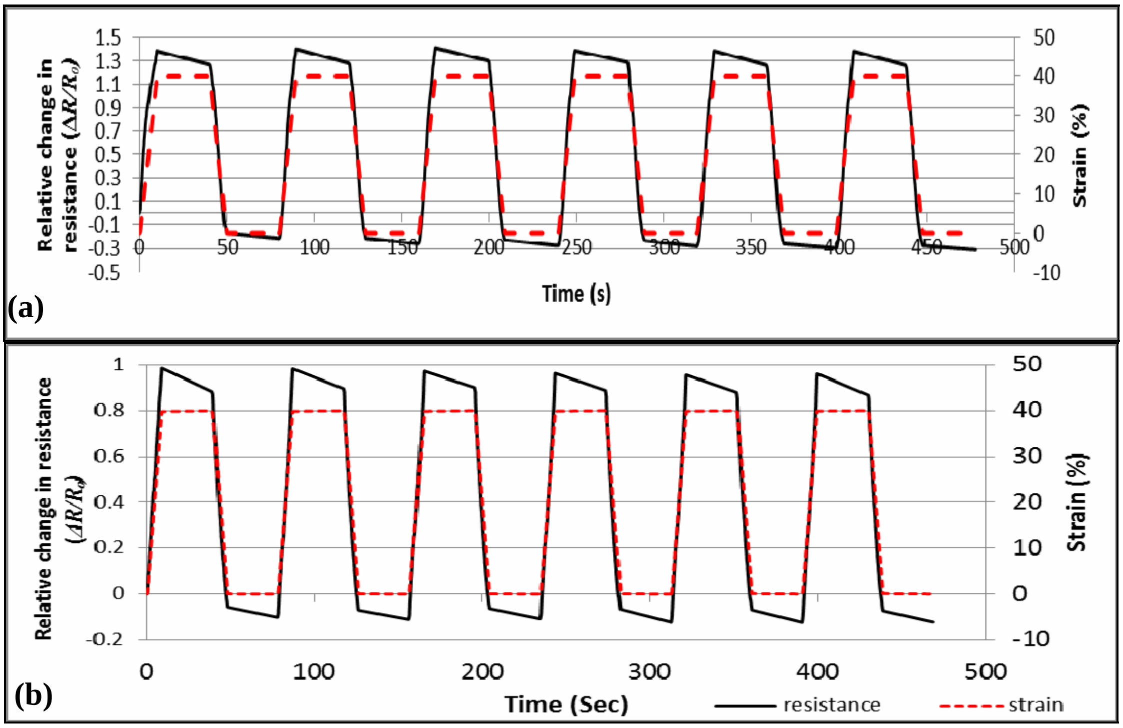

Figure 3. Quasi-static test results of two types of sensor (**a**) Type 1; (**b**) Type 2

Table 2. Change in absolute electrical resistance values of sensors during the quasi-static tests.

Type no.	Electrical resistance values(Ω) at 40 % strain	Electrical resistance values(Ω) at 40 % strain after 30 seconds	Change in resistance (inaccuracy) (%)
Type 1	281.62±0.59	268.10±0.73	4.80
Type 2	243.36±0.67	227.93±0.66	6.3

Table 3. Relative Change in electrical resistance values of sensors during the quasi-static tests

Type no.	Relative change in resistance values at 40 % strain	Relative change in resistance values at 40 % strain after 30 seconds	Change (inaccuracy) (%)
Type 1	1.384±0.003	1.273±0.006	8.02
Type 2	0.975±0.005	0.886±0.005	10.59

Table 4. Effect of crosshead speed on the hysteresis values

Cross-head speed	Maximum hysteresis values (%)
60 mm/min	6.216±0.024
120 mm/min	5.796±0.024
240 mm/min	4.826±0.035
480 mm/min	3.19±0.019

As it is evident from Table 4, when the crosshead speed increased, the electrical hysteresis values of the sensors decreased. Less relaxation time for sensors under the high crosshead speed while more relaxation time for sensors under low crosshead speed could be the possible explanation of this phenomena.

Table 5 shows the ANOVA results for linearity of the samples at the various crosshead speed. In this case, linearity defines how well, over a range of strain sensor's electrical resistance consistently changes. Here, the average column presents the coefficient determination (R^2 value) of the strain-resistance regression curve of the knitted sensor, tested at different crosshead speed. For instance 480 mm/min crosshead speed produces an average linearity of R^2= 0.99106. Considering the F, P-value and F critical values of ANOVA test results, it can be conclude that crosshead speed could affect the linearity of the sensor significantly. The F value is found to be higher than the F critical value, it is considered that there is a significant difference between tested samples.

Table 5. ANOVA results for linearity of the sensors.

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
480 mm/min	5	495.53	99.106	0.00028
240mm/min	5	494.15	98.83	0.00085
120 mm/min	5	492.44	98.488	0.00077
60mm/min	5	495.99	99.198	0.00277

ANOVA

Source of Variati	SS	df	MS	F	P-value	F crit
Between Grou	1.528815	3	0.509605	436.4925054	1.49688E-15	3.238871517
Within Group	0.01868	16	0.0011675			
Total	1.547495	19				

Table 6. ANOVA results for gauge factor in response to applied crosshead speed.

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
480 mm/min	5	21.41	4.282	0.00447
240mm/min	5	21.38	4.276	0.00418
120 mm/min	5	21.19	4.238	0.00127
60mm/min	5	20.97	4.194	0.00473

ANOVA

ource of Variatic	SS	df	MS	F	P-value	F crit
Between Grou	0.024775	3	0.008258333	2.25483504	0.121307158	3.238872
Within Groups	0.0586	16	0.0036625			
Total	0.083375	19				

Table 6 presents ANOVA results of gauge factor (sensitivity) of the sensor samples at the various crosshead speed. According to the Table 6, the difference between the gauge factor values of the sensors under the different crosshead speeds is found to be insignificant. In this case, F critical value is higher than the F value. Thus, there is no significant difference found between the tested samples in terms of gauge factor values. Therefore it can be concluded that speed has no effect on the sensitivity of the knitted sensors.

This study could help to improve the development of sensors targeted to be utilized for measurement of respiratory rate and human body joint extension i.e. elbow, knee for sports training or medical purposes or they could be part of soft robotic technology.

Future work include the investigation into the performance of proposed knitted sensors made of different coated yarn and developed on different gauge of machine. i.e. Investigation into the effect of flat-bed knitting machine gauge on knitted sensor performance; Monitoring of human body movement via the proposed sensor i.e. elbow and knee movements; Development of “Smart-Garments” using whole garment technology with exact positioning of sensing area and transmission lines using intarsia techniques; Wireless integration of a Smart-Garment system into a commercially available processor which is specially designed for smart textile applications; Testing of the sensors under different climatic conditions and after laundering as variation in temperature and humidity could influence the performance of the knitted sensors.

5. CONCLUSIONS

This study investigates the effect of different mechanical test conditions on the sensing properties of knitted strain sensors. Two different types of sensors were produce on a computerized flat bed knitting machine by using two different elastomeric yarns, i.e., 800 dtex and 570 dtex while keeping the yarn feeding tension as 8 cN. Quasi-static experimental results proved that sensors produced with low yarn extension capability show less imprecision in terms of electrical resistance values. Variation in crosshead speed also affected the sensor properties. The maximum hysteresis values of the sensors were found to be reduced in response to an increased strain application rate. Sensor linearity was also found to be affected by the strain rate, but no method was found to the establish correlation between speed and linearity through analysis of the ANOVA test results. Gauge factor values were not affected by changes in crosshead speed. It is concluded that testing conditions could play significant role in the characterization of knitted strain sensors and should be uniform /standardize for comparison of strain sensors developed by various researchers. This study could help to improve the development of strain sensors which are aimed for the measurements of respiratory efforts and the body extensions.

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