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Effect of Elasticity on Electrical Properties of Weft-Knitted Conductive Fabrics

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Abstract
Because of softness and lightness, various flexible sensors have attracted extensive attention and been widely studied. Sensing mechanism of most wearable sensors is derived from an elastic substrate, such as fabric or polymer materials. Although the mechanical-electrical performance of several flexible sensors has been reported, including sensitivity, linearity hysteresis and repeatability, research on the effects of substrate elasticity on sensor capacity is scarce. In this paper, the impact of spandex content, washing and ironing processing on the elasticity of weft knitted sensors was investigated by the constant- extension test method. Afterwards, differences in sensing properties between diverse elastic sensors under single as well as repeated stretch were reported. The experimental results showed that spandex content does influence the elasticity of knitted fabric, which has a further great effect on sensing properties. A highly elastic sensor is capable of detecting large-scale human motions, while sensors with lower elasticity are opposite, which demonstrates that elastic sensors can be designed and chosen to meet the requirements of detecting and monitoring distinct human motions.

Key words: *elasticity, weft knitted fabric, sensing performance, flexible sensors.*

Introduction

Due to many advantages such as softness, small size and light weight, conductive flexible sensors monitoring human physiological signals have attracted extensive attention recently. Strain sensors account for a considerable amount among wearable sensors, which are mainly generated by coating conductive material [1-3] on the surface of fabrics, or made with conductive materials fabricated using conductive yarns, etc. For the latter, the elongation of yarn or deformation of fabric will generate resistance change, thereby they can realise functions of sensing and monitoring human motions. Many types of elastic sensor have been reported, such as stress sensors exhibiting various sensing properties by covering single or multi-layer graphene on different elastic yarns [4], where it was found that the piezoresistive response of sensors are dependent on the yarn structure and that sensors with high stretchability were capable of detecting large-scale motion. Zhang [5] et al. prepared three kinds of polypyrrole conductive fabrics based on cotton spandex/polyester fabric by the in-situ polymerisation method, and the hysteresis in response was found in a static test of the upper limb motion. Tadesse [6] used coating and impregnation treatment to cover nylon/lycra knit fabric with PEDOT:PSS to prepare conductive elastic fabric, and found that the fabric resistance would gradually increase after repeated stretching. Wang [7] prepared a knitted flexible sensor using silver-plated nylon yarn, nylon/spandex core yarn, and elastic nylon yarn, and found that elastic flexible sensors can meet the requirements of use under small repeated strain. Although the mechanical-electrical performance of several elastic sensors have been reported, including the working range, sensitivity, linearity hysteresis and repeatability, research on the effects of substrate elasticity on sensor capacity is scarce.

Monitoring human motions requires that sensors can establish joint or skin variation immediately and systematically. Elastic fabric is soft, flexible and can fit human skin well, therefore it is a good material for generating wearable sensors. Extensity determines the comfort level of fabric sensors and the working range, while elasticity influences the frequency the fabric sensor can be worn and the sensing performance. While knitted fabrics are worn, they generate elastic and plastic deformation. Elastic deformation includes rapid elastic deformation and slow elastic deformation. The former refers to the deformation that can be recovered immediately after the applied load disappears, while the latter refers to the deformation that slowly recovers after the load disappears. Plastic deformation means deformation that cannot be restored afterwards. For fabrics with better elasticity, less plastic deformation will be produced during repeated wearing.

Monitoring different human bodies needs various sensor working ranges, for instance, identifying the knee joint requires a large strain of fabrics of nearly 60%, while for the finger joint it is just

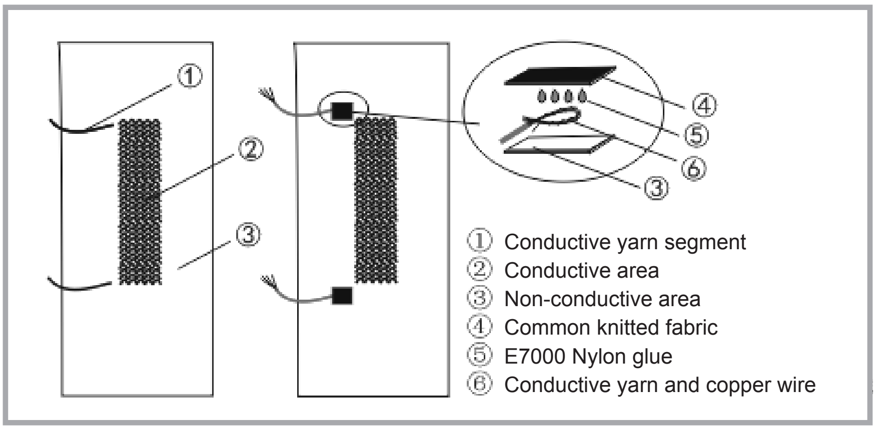

Figure 1. *Schematic diagram of knitted sensor configuration.*

Figure 2. *Photo of connection for electrical performance test.*

30%. Considering the working range and repeatability, it is necessary to study the elasticity of fabric sensors. In this paper, elastic sensors were manufactured from silver plated nylon yarn and composite yarns of different spandex content. After comparing the two groups, which included washing processing and non-treatment, the elasticity of each sensor was investigated. In addition, sensing property differences between sensors of diverse elasticity were observed under single-stretch and repeated-stretching conditions.

Experimental details

Materials

Sensor materials included 20/75 Nylon/spandex composite yarn (fineness of nylon – 83 dtex, that of spandex yarn – 22 dtex), 40/75 Nylon/spandex yarn, 70/30 Nylon/spandex yarn and high elastic polyester yarn (fineness – 333 dtex), silver plated nylon filament yarn (fineness – 333 dtex, number of monofilaments – 48, conductivity – 5.5 oum/cm). Experimental equipment included a SHIMA Seiki SWG 061N-15G Computer Flat Knitting Machine (gauge – 15), a WENZHOU Darong Electronic Fabric Mechanical Analysis Machine (FMAM, machine type – YG (B) 026ET), and a Nikon E100 biological microscope.

Fabrication of conductive weft-knitted fabric sensors

Many factors influence the elasticity of weft knitted fabrics, such as fabric structure, fabric density, content of elastic fibres, and finishing process. Herein, conductive sensors were knitted with a plating stitch structure on a flat knitting machine. In order to obtain sensors with various elasticity, composite yarns of diverse spandex content were selected as grounding yarns in the whole fabric, while silver-plated yarn was chosen as plating yarn to fabricate a conductive area by the knitting method named intarsia, which contains 5 wales and 50 courses. Specifications of the elastic conductive weft knitted fabric obtained are shown in ***Table 1***. Three samples of each kind were manufactured during this research.

Considering that people usually wash and iron common fabric in daily life, to investigate whether the washing process has a significant effect on the elasticity of knitted sensors, two group of samples were chosen to compare. In Group F, conductive knitted sensors were processed under conditions including normal water washing (40 °C, 10 minutes), drying (120 °C, 15 minutes), humidity conditioning (normal temperature and humidity, for more than 24 hours), and ironing. The untreated samples were named as Group E.

In addition, through intarsia knitting, excessive silver plated yarns of the conductive area were exposed. In order to detect resistance stably in the future and minimise the negative effects of pulling two ends of the sensor, exposed yarns were connected to an electric wire. In addition, a patch of common fabric was adhered to the fabric substrate tightly using E7000 nylon fabric glue. The configuration of flexible sensors is illustrated schematically in ***Figure 1***.

Elasticity test of flexible sensors

Common ways of determining the elasticity of elastic fabrics include the fixed-elongation and fixed-load methods. Herein, the latter was selected, where the constant elongation was set to 20%, the clamping distance to 100 mm, the stretching speed to 100 mm/min, the pre-tensioning force to 1N, the stagnant time to 60 s, the recovery time to 180 s, and the number of stretched cycles was 5 times. All the sensors manufactured were measured on an FMAM, where three samples of one kind of sensor were tested and their elastic recovery rate averaged to compare elasticity.

Sensing performance of flexible sensors

The FMAM was used to perform single and repeated stretching in the longitudi-

Table 1. *Specifications of samples obtained.*

Sample number	Plating yarn		Ground yarn in all fabric	Wales per centimeter		Courses per centimeter	
	Non-conductive area	Conductive area		Group E	Group F	Group E	Group F
T0	High elastic polyester yarn	Silver plated nylon filament yarn	None	7.1	7.5	10.2	11.0
T1			20/75 Nylon/spandex	7.1	8.3	11.8	13.4
T2			40/75 Nylon/spandex	7.1	8.3	13.0	15.4
T3			70/30 Nylon/spandex	7.1	8.6	13.8	16.5

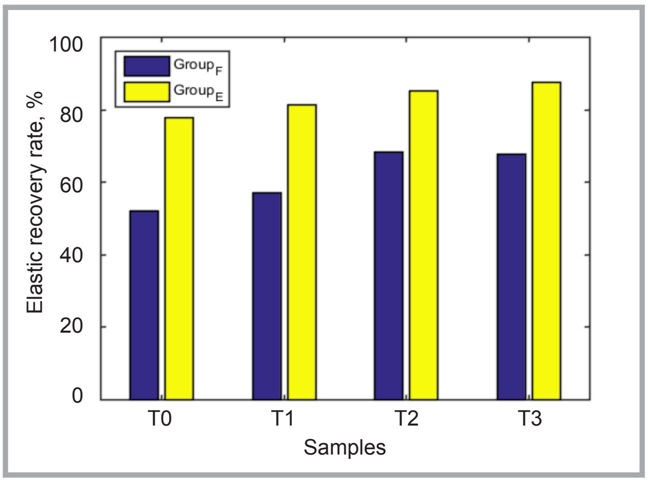

__Figure 3.__ Comparison of sensors after the washing process and those untreated.

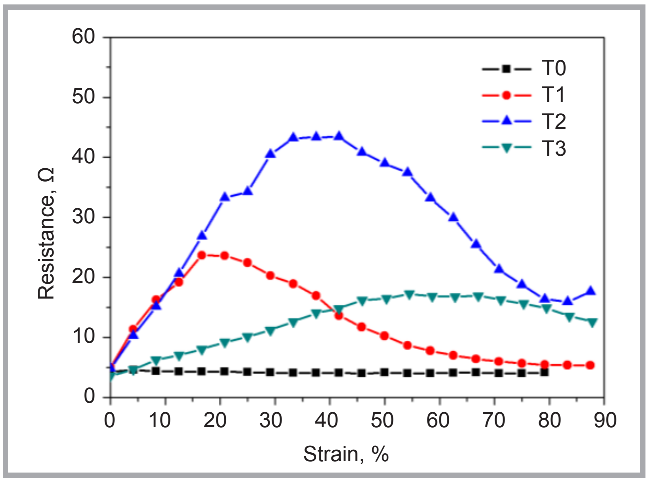

__Figure 4.__ Resistance change of four strain sensors.

nal direction of different elastic knitted sensors. In accordance with fabric extensibility, elongation was set as 80% during a single stretch, with a stretch speed of 100 mm/min. During the repeated stretching, elongation was chosen as 50% and the stretch speed as 200 mm/min. The number of repeat cycles were 40, 80, and 120 times, respectively. Through single and repeated stretching processes, the real-time resistance was recorded using self-developed software, where values were abstracted to origin 8.0 software to draw a curve for observation. A device connection photo of the electrical performance test is shown in ***Figure 2***.

Results and discussion

Elasticity contrast of flexible sensors

Figure 3 shows a comparison of samples having undergone washing and drying processes as well as with untreated ones. There was an obvious difference between the elasticity of Group E and Group F i.e. sensor samples after washing and drying exhibited higher elastic recovery. This is because after being taken off the machine, the external construction of the fabric is not stable and spandex fibres are still under tension; therefore, the elasticity of the fabrics cannot be fully exerted. While for the sensors of Group E washing, drying and ironing treatment release the internal stress of the fabric construction and relax the fabric sensor completely. Due to these treatments, knitted sensors have a more uniform geometric morphology, which means minimum external energy. Hence, it should be known that knitted sensors containing spandex fibres should be washed and undergo the heat setting process. Here, the following experiments were carried out for samples of Group E. The distinct elasticity of several sensors is illustrated in ***Figure 3***. It is obvious that Sample T0, which contains no spandex fibre, has the smallest elasticity, while sample T3 was the best of the three elastic sensors, which demonstrates that the spandex content of the fabric visibly affected its elasticity. Hence, fabric elasticity can be controlled by adding various elastic yarns to the fabric, which is instructive for future research.

Electrical performance of flexible sensors

Single stretch test

The stretching speed applied was 100 mm/min, i.e. the fabric produced a uniform strain of 1.67% per second. The resistance value was taken every 5% from the raw data obtained and plotted on origin version 8.0. Strain-resistance curves of the diverse samples obtained are shown in ***Figure 4***.

As shown in ***Figure 4***, the diverse elastic samples have significantly different sensing behaviors during strain progress. The resistance of sample T0,which is inelastic, gradually decreases as the sample is being stretched within a range of about 1 Ω. By contrast, the resistance of samples T1,T2 and T3 present evident similar variations by stages. During Phase 1, the resistance increases directly with good linearity (e.g., 0~55% for T3), which can meet the demand of being a sensor. While in Phase 2, resistance tends to stabilise as the strain increases further (e.g., 55~68%

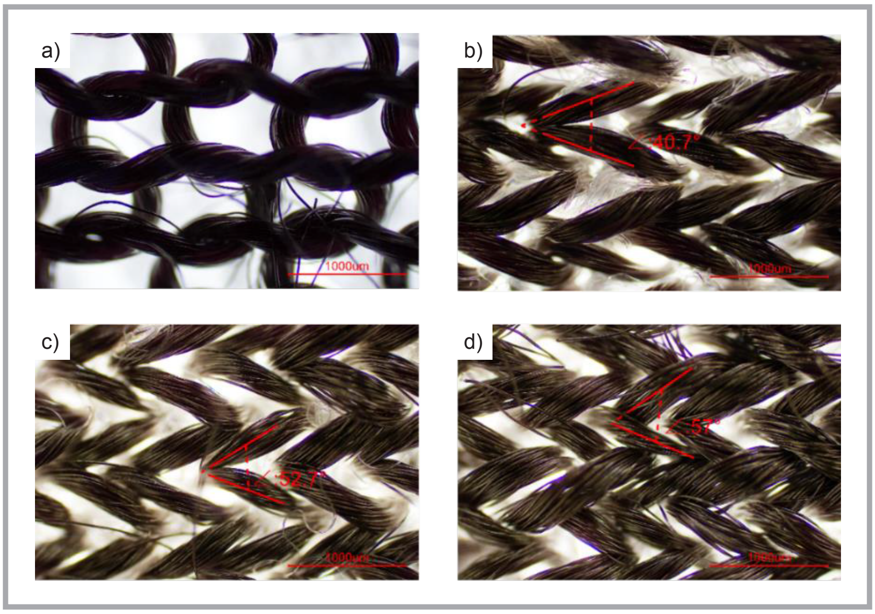

__Figure 5.__ Photographs of the conductive area of four sensors: a) Sample T0, b) Sample T1, c) Sample T2, d) Sample T3.

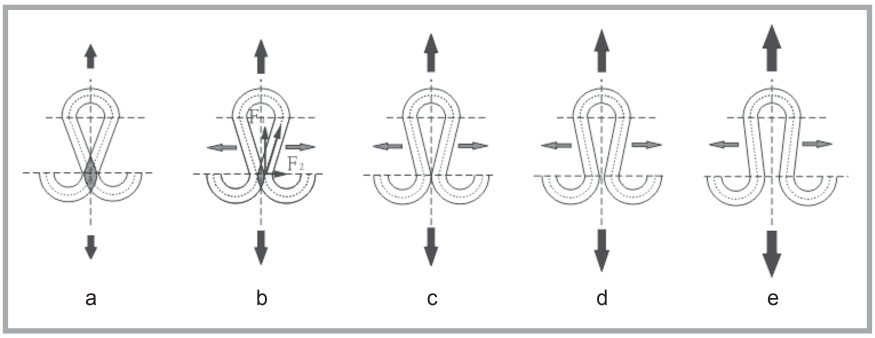

Figure 6. Simulation diagram of Phase 1 progress.

for T3). In Phase 3, the resistance begins to drop visibly (e.g., 68~90% for T3).

When choosing Phase 1 as an effective working range of knitted sensors, the results demonstrate that elasticity significantly affects the working range of strain sensors. For sample T1, it has the smallest effective range, which is about 0~18%, while for T2 it is about 0~35%. The best elasticity is shown by T3 – 0~55%. The elasticity of electric knitted sensors significantly affects their electrical performance characteristics.

To explain the phenomenon, the construction morphology of conductive areas of the elastic sensors were observed using a Nikon E100 biological microscope. As shown in ***Figure 5***, for the inelastic sensor sample (T0), loop legs are separated from each other, while elastic samples (T1,T2 and T3) present a tight loop arrangement. Comparing graphs (b), (c) with (d), it is found that knitted sensors with higher elasticity exhibited a tighter loop arrangement in the wale direction, and larger longitudinal density. This phenomenon can be attributed to the high content of spandex; theoretically, thicker spandex filament has more capacity of retracting when being tensile. Hence, sample T3 has the biggest unit density in the conductive area.

For sensors containing spandex fibres, legs of adjacent loops in the same wale are tightly in contact; therefore, contact areas exist in one loop. Bigger longitudinal density of the fabric leads directly to larger contact areas between the loops. Since deformed fabrics always tend to be in the minimum energy state during the stretching process [8-9], during initial stretching, the elastic force of the yarn is less than the contact friction between yarns; hence, the loops present extension without yarn transferring. As ***Figure 6*** shows, loop extension leads to increasing height and decreasing contact areas.

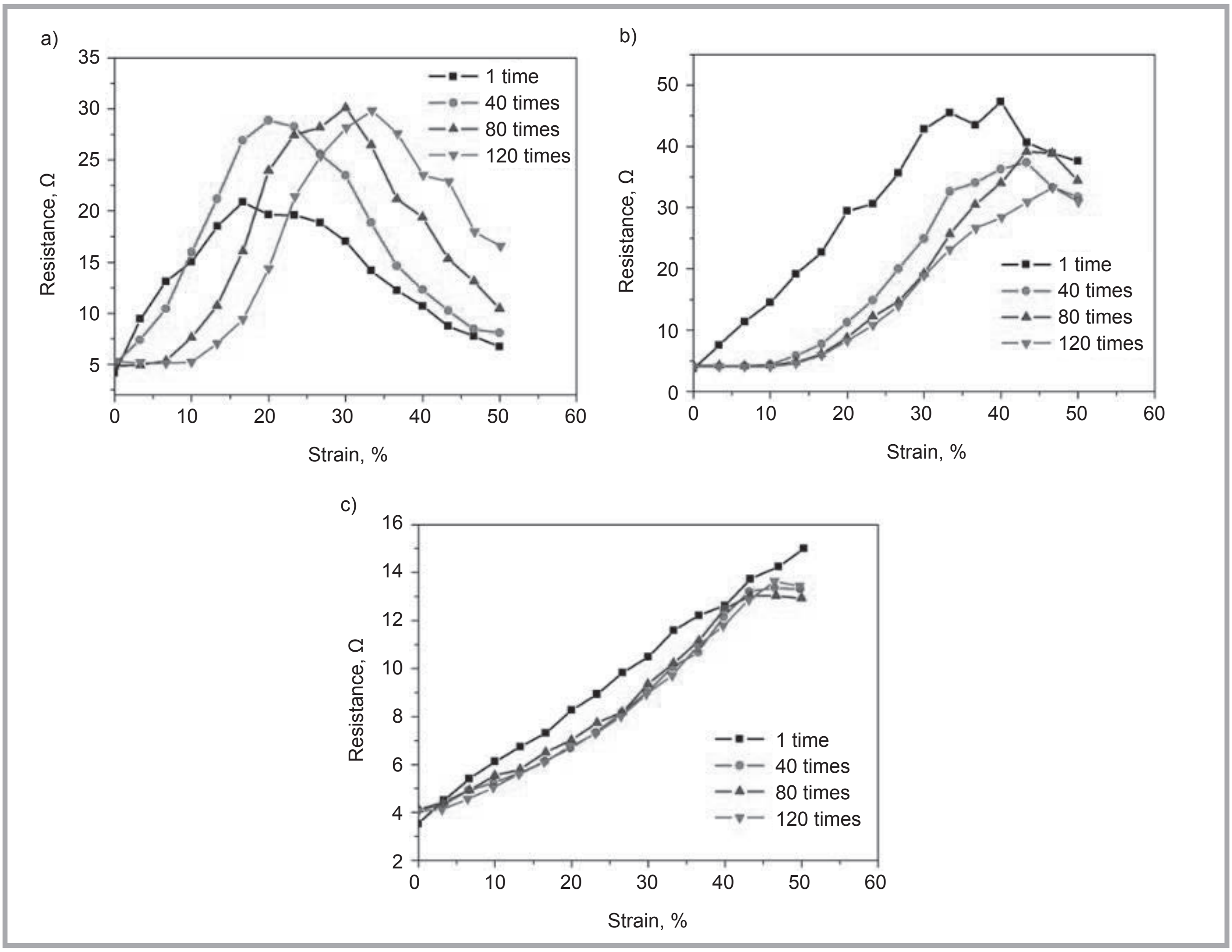

Figure 7. Stability of three elastic flexible sensors: a) Sample T1, b) Sample T2, c) Sample T3.

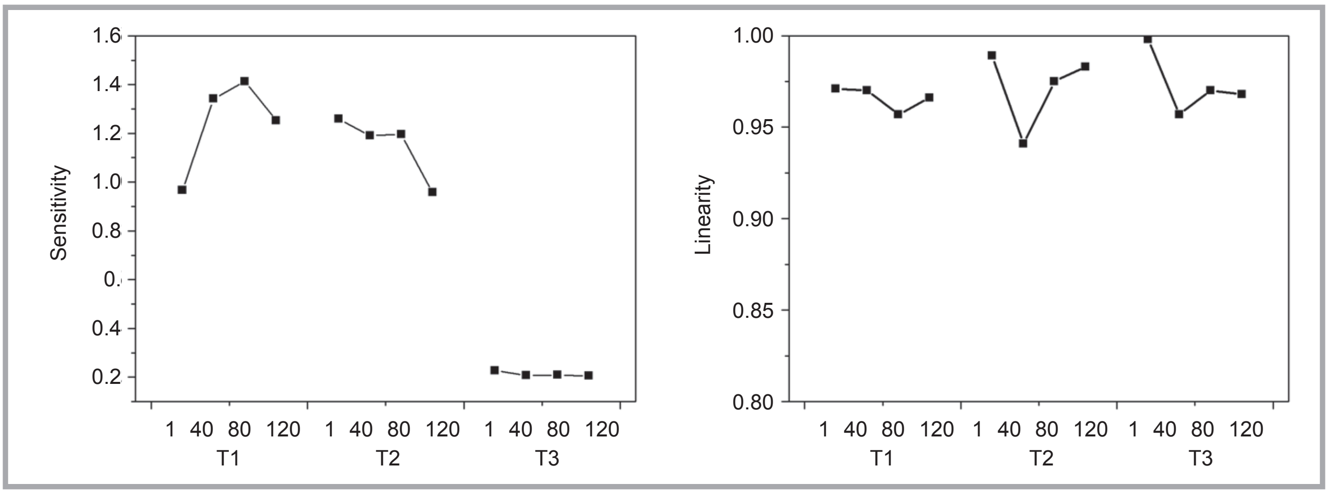

Figure 8. *Change in sensing properties of three elastic sensors.*

In (a) the loop represents a primary state before being stretched, while for b-e they demonstrate the progress of contact area reduction. For the equivalent circuit of sensors, decreasing contact areas results in the reducing of conductive paths, as a result of which the resistance of the sensor shows an upward trend, i.e. Phase 1.

As a result of choosing Phase 1 as the working range, sensors with high elasticity exhibited better capability of monitoring larger-scale human motions, such as knee, knuckle and elbow motions. When monitoring the physiological signal with a small range of changes, such as breathing, heartbeat, and throat vocalization, conductive fabric sensors with small elasticity and better sensitivity can be considered.

Repetitive stretch test

To further investigate the stability of this flexible sensor, the resistance value was measured under repeated stretching. The stretching speed was adjusted to 200 mm/min, i.e. the fabric produced a uniform strain of 3.33% per second. The resistance value was taken for every 3% from raw data obtained, and then plotted on origin 8.0. Strain-resistance curves of various samples obtained are shown in ***Figure 7***.

As shown in ***Figure 7***, for samples T1 and T2, after 40 times, 80 times, and 120 times repeated stretching respectively, a flat period occurs at the beginning of the strain-resistance curves, which demonstrates fabric fatigue. Before further stretching, certain pre-strain is required to straighten the crooked portion caused by plastic deformation. However, this phenomenon is not obvious for Sample T3. In addition, the working range of sample T3 decreased by 10% after repeated stretching, which is not obvious in T1 and T2.

For three elastic sensors, a fitted linear formula was obtained by Origin version 8.0 and their primary coefficient and correlation coefficient were obtained, the former demonstrating sensitivity and the latter exhibiting the linearity of the sensors [10]. As illustrated in ***Figure 8***, the sensitivity of sample T1 firstly increases and then decreases, while its linearity changes little. For samples T2 and T3, with better elasticity, the sensitivity decreases as the repeat increases, while linearity initially decreases and later increases; however, the overall change is small. The above phenomenon is due to the elastic fibre fatigue after repeated stretching [11], leading to the process of the extension of tight loops in the whole strain progress being shortened, and the yarn segment transfer and yarn elongation happening earlier. As a result, the electrical performance of the sensors is changed.

In practical applications, conductive fabric is embedded as a flexible sensor in certain parts of the garment, where the fabric is deformed and restored as the skin stretches and retracts during human movement, which is equivalent to repeated stretching on a fabric strength machine. ***Figure 5*** shows that conductive fabric with a lower spandex content is more prone to mechanical fatigue, hence it more easily undergoes irreversible plastic deformation when used as a flexible sensor, resulting in the failure of the smart clothing monitoring function. Therefore, conductive fabric with better elasticity is more suitable for sensor use. In addition, the structure and elasticity of smart clothing can be designed according to the purpose of sensors.

Conclusions

In summary, elastic knitted flexible sensors with diverse spandex content were fabricated, the results of which show that elastic samples have distinct resistance variations by stages during strain progress as compared with the non-elastic sample, where phase 1 can meet the requirement of the sensing function. In addition, washing, drying and ironing of samples released the internal stress of entangled loops and reformed the fabric construction, so that the elasticity of the fabric could be fully realised.

Through the fabric elasticity test, it was found that knitted samples with a higher spandex content had better elasticity, while the elasticity of flexible sensors has a significant effect on their electrical performance. The sensor sample with better elasticity had a bigger working range, i.e. the stage of realising the sensing mechanism of sensors, which is beneficial for monitoring human motions with larger joint change. By contrast, the sensor sample with smaller elasticity had a lesser range of phase 1 but better sensitivity, which can meet the demand of monitoring physiological signals with a tiny stretch of skin. Therefore, smart clothing can be designed according to the purpose of sensors.

Finally, although elasticity affects the durability and repeatability of flexible sensors, fabric fatigue occurs later in sensor samples with better elasticity, and the change in sensitivity as well as linearity is smaller during multiple stretching. Due to the thinner elastic fibres, a sample with lower elasticity is more likely to be fatigued, which will seriously affect sensing ability.

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