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Flexible textile-based strain sensor induced by contacts

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Abstract

In this paper, the contact effects are used as the key sensing element to develop flexible textile-structured strain sensors. The structures of the contact are analyzed theoretically and the contact resistances are investigated experimentally. The electromechanical properties of the textiles are investigated to find the key factors which determine the sensitivity, repeatability, and linearity of the sensor. The sensing mechanism is based on the change of contact resistance induced by the change of the configuration of the textiles. In order to improve the performance of the textile strain sensor, the contact resistance is designed based on the electromechanical properties of the fabric. It can be seen from the results that the performance of the sensor is largely affected by the structure of the contacts, which are determined by the morphology of fiber surface and the structures of the yarn and fabric.

Keywords: wearable strain sensor, textile strain sensor, flexible strain sensor, gauge factor, smart textiles

(Some figures may appear in colour only in the online journal)

1. Introduction

With the rapid development of wearable electronics, flexible strain sensors are in increasing demand for their unique elastic, wearable, and extendable properties to cover a 3D surface. In healthcare applications, for example, wearable sensors can pick up vital signals of a wearer's health in real time [1–3].

The strain sensor is one of the most widely used sensors when designing wearable systems for physiological or bio-mechanical information monitoring of the human body. It is important to integrate sensors into a wearable system for easy usage and comfortable wearing [4]. In order to pick up the strain signals such as body strain (perspiration rate, heart rate, etc), the motions of the joints, body movements, etc, the sensors should be flexible, wearable, breathable, comfortable, and non-obtrusive for daily activities. In traditional strain sensors such as strain gauges, optical fibers are not suitable for such applications due to their small measurement range and high rigidity. Owing to its unique physical and chemical properties, textile can be one of the best platforms for wearable devices [5, 6]. It is a new application of wearable strain sensors based on the structure-induced change of electrical resistance under external force [7–12]. Some flexible strain sensors have been developed and used in industry [13–15]. Conductive textiles that can measure strain or stress and that are used as wearable sensing devices have been investigated by many researchers [7, 9, 16, 17]. Textile structures made from intrinsic electrical conductive fibers such as stainless steel and carbon fibers have been demonstrated to have good sensing abilities and have been investigated by the authors' groups [17–21]. Despite the extensive progress in wearable strain sensors, very little attention has been directed at a systematic analysis of the sensing mechanism based on contact resistance caused by the textile's structure. In this paper, the sensing mechanism, structural design, fabrication, and testing of the sensor based on the contact resistance effect is described. The relationship between the sensor's properties of sensitivity, linearity, repeatability, and structure of the contact resistance is investigated theoretically and evaluated experimentally. It is found that the strain range and sensitivity increase, which is determined by factors such as the material's system and the structures of the fiber, yarn, and fabric. According to the design format and the number and materials of the contacts, the optimal textile-structured strain sensor can be fabricated based on the application situations.

Table 1. Comparison of reported textile based strain sensors.

Researchers	Sensing mechanism	Structure	Sensor material	Sensitivity (Gauge factor)	Strain range	Application
De Rossi *et al* [16]	Piezoresistive and contact effects	Knitted fabric coated with polymeric film	Polypyrrole with Lycra / cotton	−13.25 (course) −12.5 (warp)	10%	Virtual reality gloves and garments
Paradiso *et al* [12]	Piezoresistive effects	Knitted fabric	Carbon loaded rubber with lycra fabric	About 3.0 (course) About 1.7 (warp)	50%	Respiration, body movements
Kyung *et al* [9]	Piezoresistive effects	Knitted fabric	Polypyrrole with Nylon / spandex	0.42	60%	Electrotherapy
Xue *et al* [10]	Changes of the fiber dimensions	Fiber	Polypyrrole with PA6 and Polypyrrole with Lycra	About 2.0 (Ppy-PA6)	0.4%	Not specified
Wang *et al* [22]	Contact of yarn	Knitted fabric	Silver-plated yarn	About 5	10%	Wearable sensor
Dias *et al* [11]	Extension of electric conductive polymeric fiber	Knitted fabric	Carbon-filled polymeric fiber	About 0.5	14%	Displacement transducers
Tao *et al* [15]	Fiber Bragg grating	Fiber	Optical fiber	About 0.8	0.035%	Precise strain measurement
Author proposed sensor 1	Contacts of fiber/ yarn/ fabric	Single warp fabric	Carbon fiber	10 to 200 depend on fiber length	Max. 200%	Wearable strain sensor
Author proposed sensor 2	Contacts of fiber/ yarn/ fabric	Knitted fabric with laser engraved fiber	Carbon loaded fiber and nylon fiber	10 to 50 depend on laser treatments	Max. 500%	Wearable strain sensor

Table 1 gives a general comparison of some typical reported textile-based strain sensors with the current proposed sensors regarding the sensing mechanism, structure, materials, strain range, sensitivity, application etc.

2. Theoretical

2.1. Elements of contact resistance

As mentioned previously, the sensing mechanism is based on the contact resistance constructed by the textile structures. Here contact resistance refers to the electrical resistance between two physically contacted electrical conductive bodies. According to Holm theory [23], for two contacted bodies, the contact resistance can be expressed in equation (1)

$$R_k = \frac{\rho}{1.13}\sqrt{\frac{\xi H}{nF}} \tag{1}$$

Here R_k is the contact resistance of two contacted bodies and ρ and H are the resistivity and hardness of the bodies, respectively, assuming that the materials of the two bodies are the same. n is the number of the contacting points in the contact area (in macro scale, the contact surface is actually composed of many individual contact points). F is the contact force applied and ξ is a constant parameter. From equation (1) it can be seen that contact resistance is in inverse proportion to contact force F and contact number n. With the increase in contact number n and contact force F, the contact resistance will decrease accordingly. As for the textile, the relationship between the resistance and strain can be obtained if the relationship between the strain and stress and the relationship between the resistance and stress of the textiles are given. The first relationship is determined by the material properties of the textiles and the latter is determined by equation (1). Therefore, contact resistance is the key mechanism of the textile strain sensor. Hence, how to construct and arrange these contacts by textile structure is the key factor, which needs to be considered during the sensor design. In this paper, intrinsic electrical conductive materials are considered such as metal and carbon fiber due to its good environmental stability, and physical and electrical properties. In textiles, contacts exist in formats depending on the

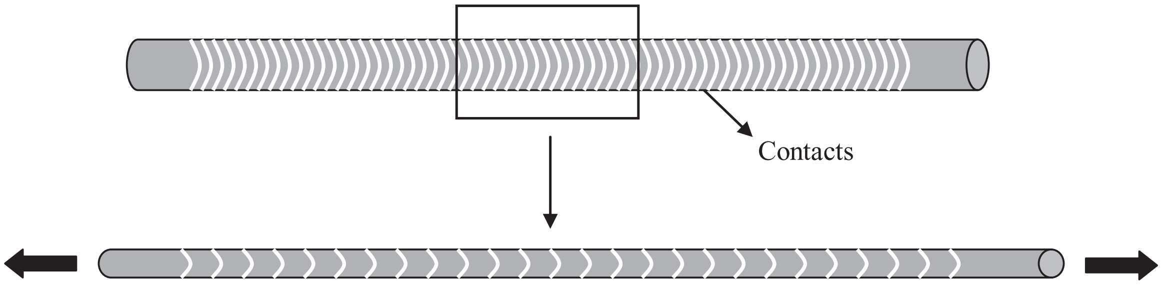

Figure 1. Contacts of the 'cracks' on the fiber surface before and after the extension of the fiber (top view).

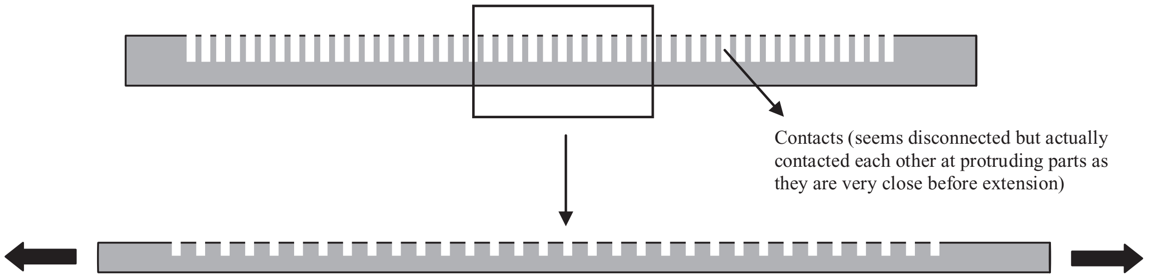

Figure 2. Contacts of the 'teeth' on the fiber surface before and after the extension of the fiber (side view).

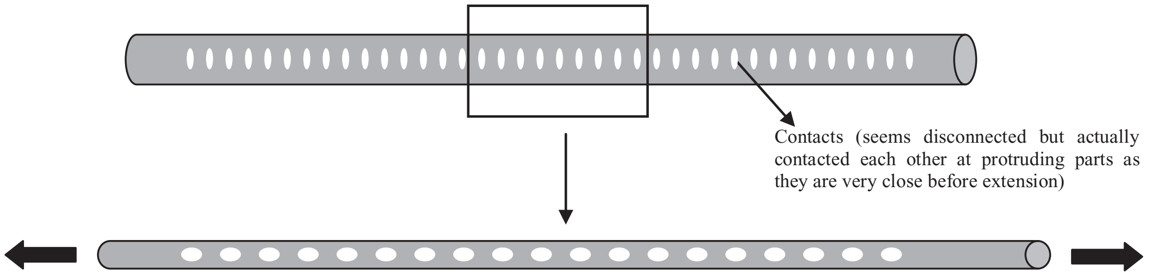

Figure 3. Contacts of 'holes' on fiber surface before and after extension of fiber (top view).

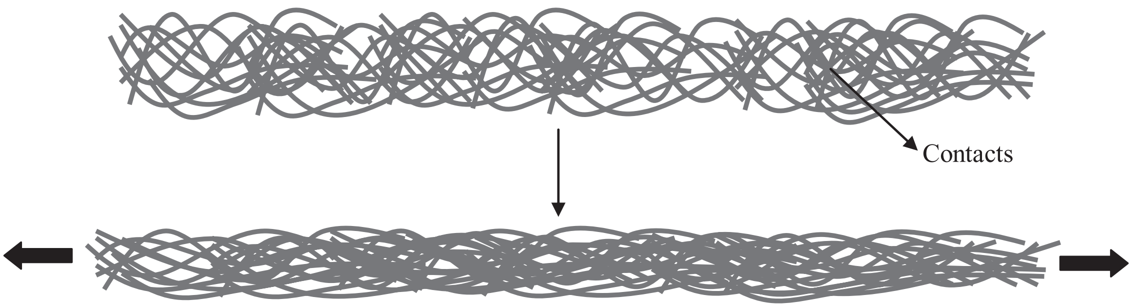

Figure 4. Fiber–fiber contacts within the yarn before and after the extension (short fiber) of the fiber.

material and structures of the textiles. In general, it exists in the following main scales.

2.2. Contacts on the fiber scale

On the fiber scale, the contacts can be random or regularly distributed 'cracks' on the surface of the conductive fibers, as shown in figure 1. This 'crack' can be achieved by different physical or chemical treatments such as plasma and liquid nitrogen treatments on the surface of the fiber. The 'crack' depth is small, so it cannot affect the mechanical properties of the fiber. An other format of contacts on the fiber scale can be conductive particle–particle contacts attached on the surface of the fiber by chemical agents or within the fiber as particles-reinforced fiber composites.

Using 'crack', for example, it will construct electrical contacts by the 'open and close' effects during the extension and recovery cycle of the fiber. Therefore, the fiber will change its resistance according to the contact number of the 'crack' during the extension and recovery cycles. The relationship between the contact number and the strain of the fiber will determine the sensitivity of the sensor. The repeatability of the textile-structured strain sensor will be determined by the recovery abilities of the fiber. The sensitivity will be governed by the shape, depth, width, and density of the contacts. Besides the formats of the 'cracks' and particles, the contacts

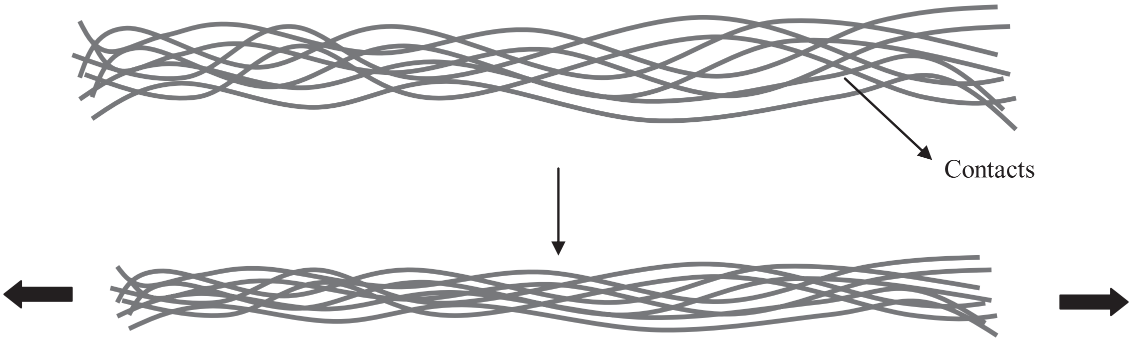

Figure 5. Fiber–fiber contacts within the yarn before and after the extension (continuous fiber) of the fiber.

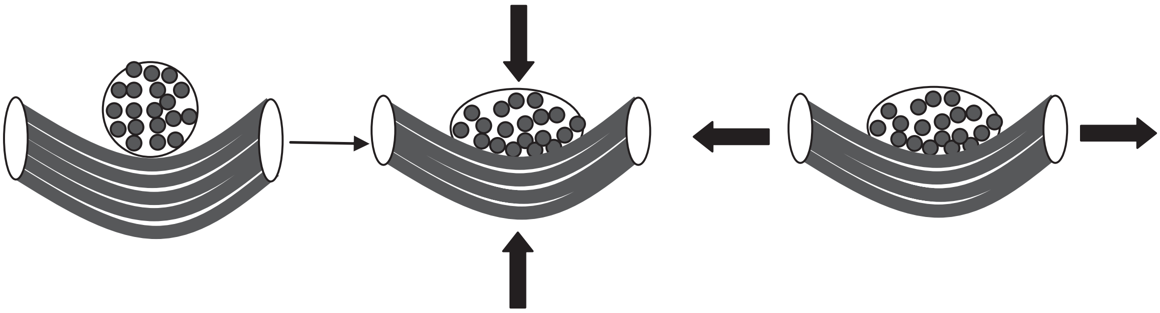

Figure 6. Yarn–yarn contacts model during deformation.

can also be in the format of special shapes such as 'comb-like' or 'holes' engraved by a laser beam, as shown in figures 2 and 3.

It can be seen from figures 2 and 3 that the 'teeth' and 'holes' before extension can create contacts of between-teeth or between-edges of holes. These contacts will change the total resistance of the fiber during the extension-recovery cycles according to equation (1). From the schematic diagrams in figures 2 and 3, the contacts seem invisible. However, there are a large number of contact points between the 'teeth' or 'edges' at small protruding parts which can be seen by microscope. Therefore, on the fiber scale, the contacts can be defined as 'small part–small part contacts'.

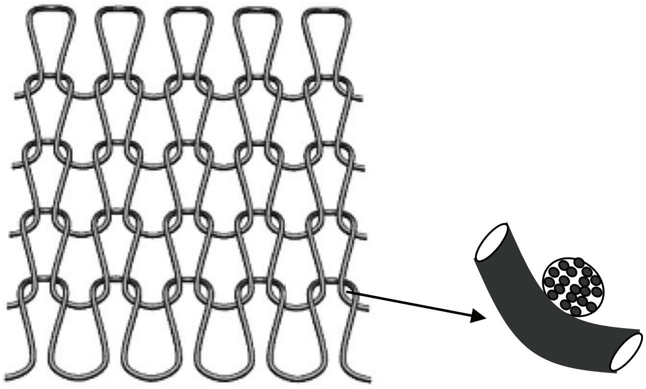

Figure 7. Yarn–yarn contacts distribution in a knitted fabric structure.

2.3. Contacts on the yarn scale

Yarn is the 3D assembly of fibers. On the yarn scale, besides the 'small part–small part' contacts on the fiber scale mentioned above, there are a large number of fiber–fiber contacts. In a yarn, whether the short fiber of a stable yarn or the continuous fiber of a filament yarn, the lateral force from twisting the yarn will cause the fibers to entangle with each other to form a yarn. This will inevitably create a large number of contacts between fibers, as shown in figures 4 and 5.

It can be seen from figures 4 and 5 that the contacts between the fibers come from the entanglement of the fibers. The twist will produce a lateral press force on the fibers, which in turn constructs the fiber–fiber contacts. The number of contacts of the short stable yarn is larger than the continuous filament yarn as the short fibers have more fiber ends. These fiber ends will introduce more fiber–fiber contacts. When the yarn is under extension, it will increase the lateral press force on the fibers. The contact resistance will decrease according to the increase of the contact force. Meanwhile, the number of fiber–fiber contacts will also increase due to the decreasing gap between the fibers. These two factors simultaneously decrease the total resistance of the yarn. If the fiber itself also has contact resistance on the fiber scale, as described in section 2.1.1, it will be a combined effect of these types of contacts.

2.4. Contacts on the fabric scale

Fabric is a 3D arrangement of fiber and yarn determined by fabric structures. Fabric structures include woven, knitted, nonwoven, etc. On the fabric scale, besides the 'small part–small part contacts' of the fiber and the fiber–fiber contacts of the yarn, there are a large number of yarn–yarn contacts. Different fabric structures will create different distributions of these yarn–yarn contacts. If simulated by circuit networks, a different circuit network can be constructed by a different

Table 2. Contacts of different scales.

Scale	Fiber	Yarn	Fabric
Contact forms	• Small part–small part	• Smallpart–small part • Fiber–fiber	• Small part–small part • Fiber–fiber • Yarn–yarn
Fabrication methods	Laser, plasma, low temperature, composition, etc	Spinning of the yarn	Knitting, weaving, etc

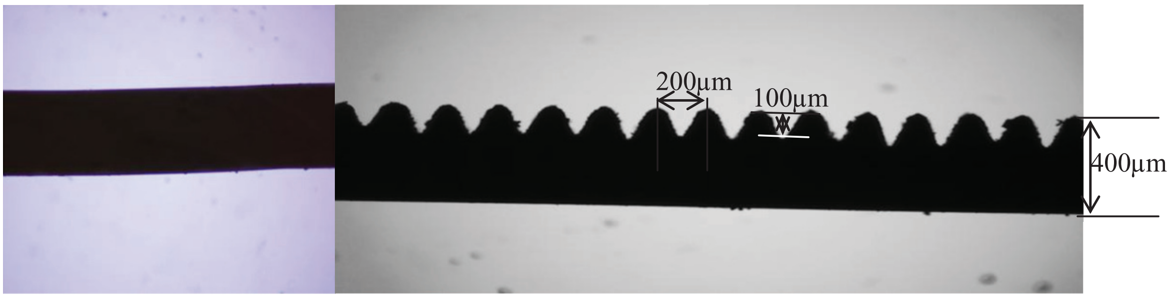

Figure 8. Orignal fiber and contacts of the 'teeth' on the fiber surface by laser treatment.

fabric structure accordingly. This circuit network can affect the properties of the fabric sensors. As for an analysis of the structures, although they are varied they can be simply simulated by the combination of a basic yarn–yarn contacts model, as shown in figure 6.

Figure 6 shows the cross-section model of two contact yarns and its deformation after pressure and extension of the fabric. Besides fiber–fiber contacts on the yarn scale, it is clear that the resistance of the two contact yarns is mainly determined by the direct contact fibers at the contact interface. The actual contact number of the fiber will increase with the increase of the pressure or the extension of the fabric because more fibers will transfer to the direct contact interface. It will decrease the total resistance of the yarn–yarn contact. For a fabric, there is a distribution of such yarn–yarn contacts although the fabric structure is complex and varied, as shown in figure 7.

Use the basic knitted fabric structure shown in figure 7 as an example, it can be seen that the yarn–yarn contacts are arranged in a matrix determined within the fabric structure. Different fabric structures can construct different circuit networks composed of yarn–yarn contact resistances. Therefore, the contacts will be the key sensing element of textile sensors made from intrinsic conductive material. The contacts for the different scales are shown in table 2.

3. Experimental

3.1. Material

3.1.1. Contacts on the fiber scale. In this paper, commercial carbon loaded silicon rubber is used for the contacts investigation on the fiber scale due to its large strain range and repeatability. Meanwhile, it is also easy for laser treatment. The diameter of the fiber is 400 μm. The resistance per unit length is 350 Ω cm^{-1}.

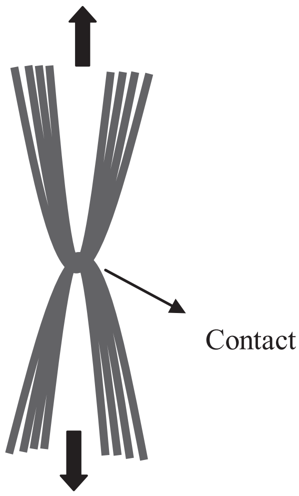

Figure 9. Yarn–yarn contact on the fabric scale.

3.1.2. Contacts on the yarn scale. The material is carbon yarn because of its high bending rigidity and environmental stability. The high bending rigidity will help improve the repeatability of the sensor after deformation. It is a polyacrylonitrile (PAN)-based fiber for oxidization in air at 200 °C and then carbonization at the temperature of 1000 °C in an inert atmosphere (nitrogen) to finally be carbon yarn.

3.1.3. Contacts on the fabric scale. The fabric is the same material as the yarn mentioned above.

3.1.4. Textile-structured strain sensor. In this paper, short carbon fiber is used to create more contacts at the fiber ends.

3.2. Fabrication

3.2.1. Contacts on the fabric scale. Laser treatment is employed to 'slice' the fiber into a 'comb-like' surface to

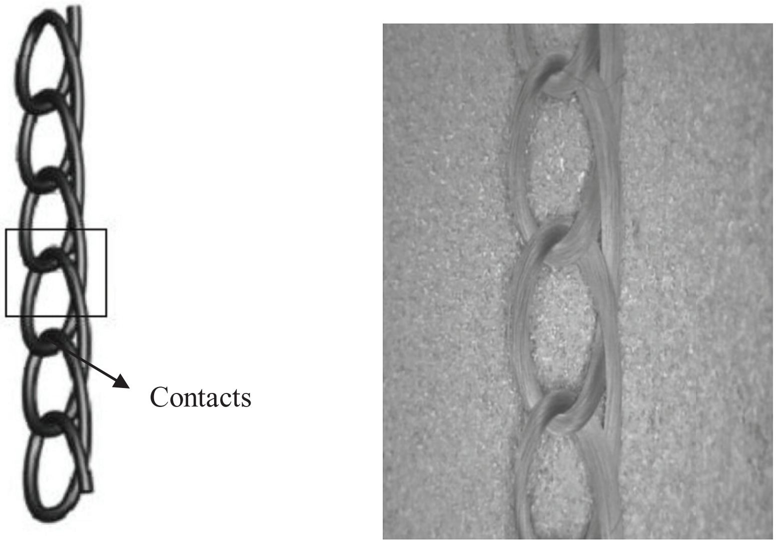

Figure 10. Single warp loop structure of the fabric.

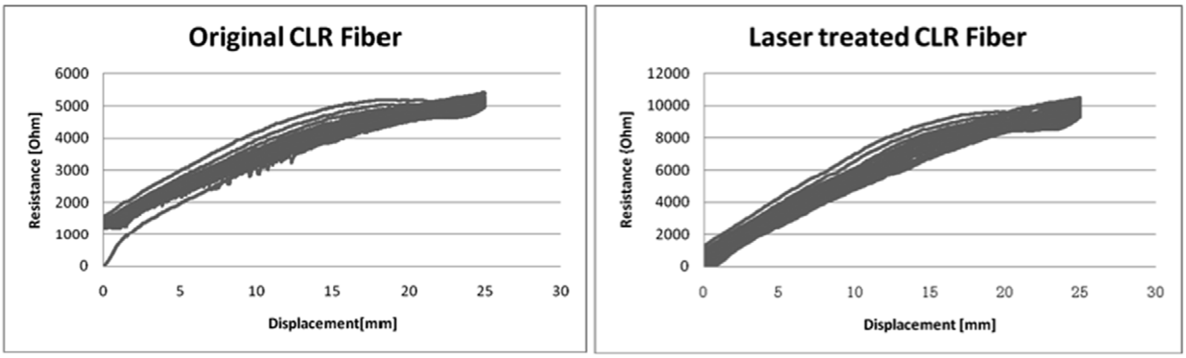

Figure 11. Resistance-strain relationship of the original fiber and treated by laser.

create contacts between the 'teeth', as shown in figure 8. The tooth depth is 100 μm and the distance between the teeth is about 200 μm. The diameter of the fiber is 400 μm. The fiber is placed on the bed of the laser machine to be engraved under a specified energy value.

3.2.2. Contacts on the yarn scale. In order to create more fiber–fiber contacts, stable short fiber spinning yarn is used in the current research with a yarn count of 60 s.

3.2.3. Contacts on the fabric scale. Two short fiber stable yarns are 'hooked' together to investigate the electromechanical properties of the contacts on the fabric scale, as shown in figure 9.

3.2.4. Textile-structured strain sensor. For the textile strain sensor, textile structure is the first factor to be considered as it will affect the connect format of the yarn–yarn contacts. It will in turn affect the sensitivity of the fabric sensor. Theoretically, by a circuit analysis of the simulated fabric structure, the series connected connection of the contacts can improve the linearity of the sensor if the strain-resistance relationship of each contact is linear (as analyzed in section 4.4). Therefore, the single warp loop fabric structure is investigated in this paper, as shown in figure 10. The yarn–yarn contacts are in a series connection to improve the linearity and sensitivity.

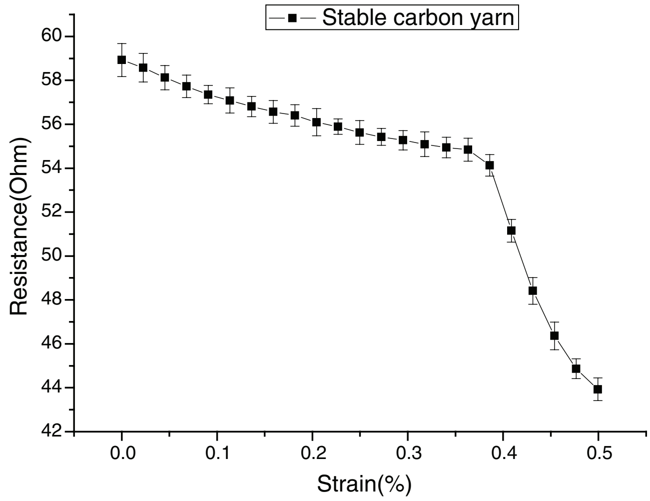

Figure 12. Resistance-strain relationship of short fiber (stable) carbon yarn.

3.3. Testing

To investigate the electromechanical properties of the contacts, i.e. the relationship between the resistance and strain/stress of the contacts, the resistances are recorded by multimeter and the strain/stress is measured by an Instron Universal

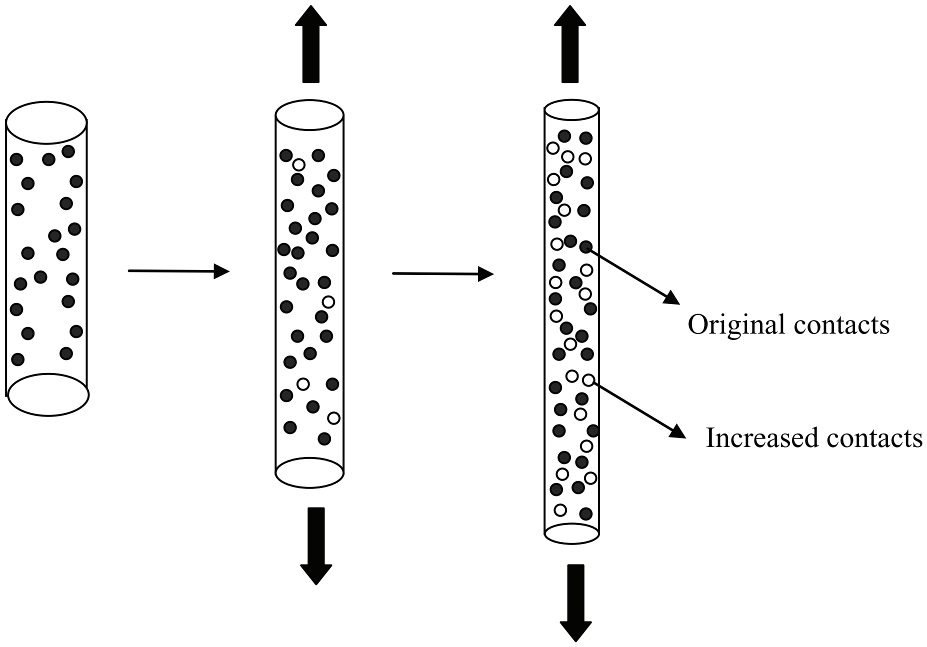

Figure 13. Fiber–fiber contacts during the extension of the stable yarn.

Material Tester. The fiber/yarn/fabric is stretched at given crosshead speeds with its two ends clamped on the load cell of the Instron Tester.

4. Results and discussion

4.1. Electromechanical properties of contacts on the fiber scale

Figure 11 shows the resistance-strain relationships of the carbon loaded silicon rubber before and after laser treatments for five extension-recovery cycles, respectively. It can be seen that the sensitivity (gauge factor) of the fiber treated by laser has been improved dramatically compared to the original fiber from 10.6 to 24.8 calculated by equation (2) due to the presence of surface contacts.

$$G = \frac{\Delta R/R}{\Delta L/L} \tag{2}$$

Here R is the resistance and L is the length of fabric. The gauge factor of the original fiber is smaller compared to the laser treated one. The sensitivity of the original fiber is mainly induced by the 'quantum effect' of carbon black particles in the polymer system of the fiber material. The laser engraved surface contacts increase the sensitivity and modify the strain–stress relationships of the fiber, in turn changing the repeatability of sensor. It can be seen that the resistance increases gradually with the extension of the fiber, which is due to the increase of the gaps between the 'teeth', which decrease the number of contacts.

4.2. Electromechanical properties of contacts on the yarn scale

Figure 12 shows the resistance-strain relationship of yarn made from carbon short fibers. Different to the 'small part–small part' contacts on the fiber scale, here it is fiber–fiber random contacts in the yarn. It is more difficult to control the distribution of these between-fiber contacts due to the complex spinning processes. It can only give statistical parameters of this distribution determined by yarn parameters such as fiber length, yarn diameter, fiber diameter, the twist factor, etc. It is obvious that the resistance decreases with the increasing strain. There are two stages on the curve, a slow decrease stage before the strain of 0.4% and a sharp decrease stage after that. This is because the extension of the yarn is mainly caused by the straightening of the short fibers at the first stage. After full straightening, there will be lateral pressing against the fibers at the second stage, which increases the between-fiber contacts dramatically. By using 'dots' to simulate the contact resistances, the processes during the extension are shown in figure 13. At the first stage, due to the straightening of the fibers, there are fewer increased contacts compared to the second stage of the pressure-induced more contacts.

4.3. Electromechanical properties of contacts on the fabric scale

Figure 14 shows the resistance-strain relationship of two 'hooked' yarns made from carbon short fibers, as shown in figure 9. It is clear that the resistance deceases linearly with the increasing strain. The decrease of resistance comes from two resources. The first is the yarn–yarn contacts, as shown in figure 12, and the second is the increase of the surface contacts of the two 'hooked' yarns. The second resource is the main reason, as the extension of yarn is quite small, as seen in figure 12, in order to avoid damage to the yarn. The extension mainly comes from the dimensional change at the contact surface of the two contact yarns. When under extension, more and more fibers will 'move' to the contact

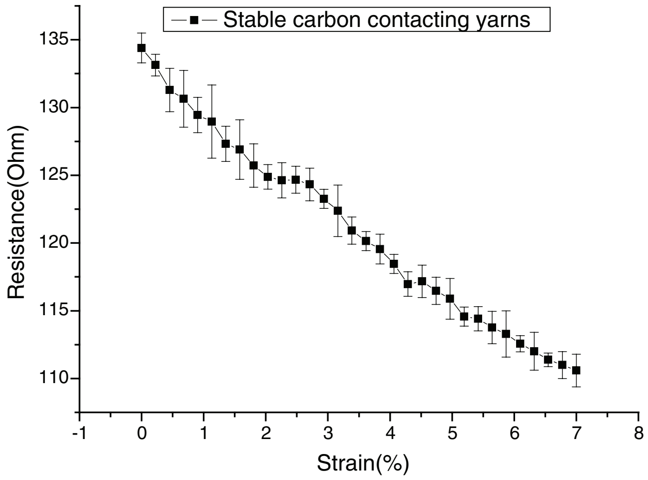

Figure 14. Resistance-strain relationship of two short carbon fiber contact yarns.

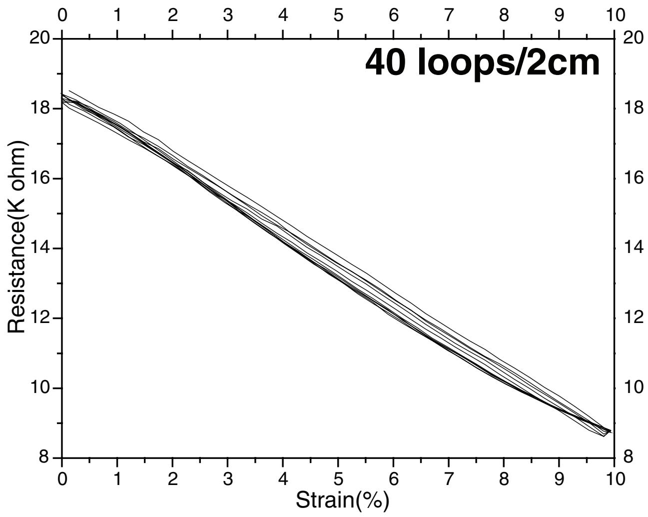

Figure 15. Resistance-strain relationship of the single warp fabric strain sensor.

surface, as shown in figure 6. This shows a relationship with high linearity.

4.4. Electromechanical properties of the textile-structured strain sensor

Figure 15 shows the five cyclic resistance strain relationship of a single warp fabric made from short carbon yarns, as shown in figure 10 with a loop density of 20 loops cm^{-1}. It can be seen that the resistance decreases with the increase in strain linearly. As this fabric structure is the series connection of single yarn–yarn contacts. If simulated by a circuit, as shown in figure 16, the yarn–yarn contact resistances are in series connections if the length resistances of the yarn are ignored.

The advantage of series connections is that if each strain resistance of yarn–yarn contact is linear, as expressed in equation (3).

$$\begin{aligned} R_1 &= a_1\varepsilon + b_1 \\ R_2 &= a_2\varepsilon + b_2 \\ &\cdots \\ R_n &= a_n\varepsilon + b_n \end{aligned} \tag{3}$$

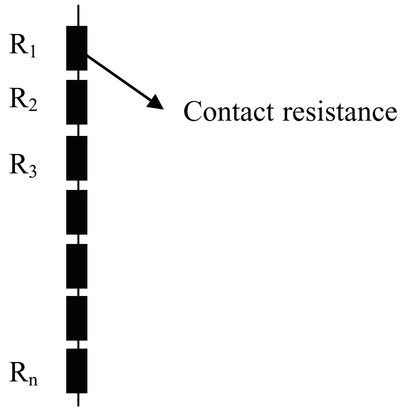

Figure 16. Simulated circuit of a single warp fabric.

The total resistance strain relationship of the fabric will also be linear as expressed in equation (4).

$$\begin{aligned} R &= R_1 + R_2 + \ldots + R_n \\ &= (a_1 + a_2 + \ldots + a_n)\varepsilon + (b_1 + b_2 + \ldots + b_n) \\ &= A\varepsilon + B \end{aligned} \tag{4}$$

Therefore, it is reasonable that the linear curve of fabric strain sensor comes from the series connection of the yarn–yarn contacts, as shown in figure 14. Fabric is the structural assembly of fiber and yarn. By circuit network analysis, the fabric structures can be proposed according to the actual application requirements such as sensitivity, linearity, repeatability, hysteresis, flexibility of the sensor, etc. The theoretical analysis and experimental evaluations of different scales are shown in table 3.

The sensor designer can choose which scale of contact will be emphasized based on the properties of the wearable strain sensor. It is a systematic design process. Nevertheless, contact resistance is the key sensing mechanism for intrinsic electrical conductive materials.

5. Conclusion

In this paper, a textile-structured flexible strain sensor made from intrinsic electrical conductive fiber is proposed. The sensor can be used in wearable systems for the monitoring of physiological or biomechanical parameters. The sensing mechanism is based on the contact resistances on different scales such as fiber, yarn, and fabric. The electromechanical properties of the contacts on the fiber, yarn, and fabric scale, as well as the textile structure strain sensor are investigated theoretically and experimentally to find the key parameters when designing the fabric sensor. It can be concluded that:

(1) Contacts are the key elements when designing a fabric strain sensor made from intrinsic electric conductive materials. The design of the fabric structure to arrange the contacts in optimal formats is the first factor to be considered.
(2) On the fiber scale, the ‘crack’ on the surface of the fiber will construct electric contacts by the ‘open and close’ effects during the extension and recovery cycle of the fiber. The shape, depth, width, density, etc can also affect the sensitivity of the sensor.

Table 3. Theoretical analysis and experimental evaluations of the different scales.

Scale	Fiber	Yarn	Fabric
Contact forms	• Small part–small part	• Small part–small part • Fiber–fiber	• Small part–small part • Fiber–fiber • Yarn–yarn
Theoretical analysis	Change of resistance due to the contact number of small part–small part contacts	Change of resistance due to the contact number of small part–small part contacts and fiber–fiber contacts	Change of resistance due to the contact number of small part–small part contacts and fiber–fiber direct contacts in the contact surface of two yarn constructed by the fabric structure.
Experimental results	Figure 11. Resistance-strain relationship of laser treated CLR fiber	Figure 12. Resistance-strain relationship of short fiber (stable) carbon yarn	Figure 15. Resistance-strain relationship of carbon fiber single warp fabrics

(3) On the yarn scale, besides the 'small part–small part' contacts of the fiber, there is a large quantity of fiber–fiber contacts. The lateral force will cause the fibers to entangle with each other to form a large number of contacts between the fibers.

(4) On the fabric scale, besides the 'small part–small part' contacts of the fiber and the fiber–fiber contacts of the yarn, there are a large number of yarn–yarn contacts. Different fabric structures will construct different distribution formats of yarn–yarn contacts. This will affect the circuit of the fabric and determine the electromechanical properties of the fabric.

(5) By a circuit network analysis, the fabric structures can be designed according to the actual application requirements such as sensitivity, linearity, repeatability, hysteresis, flexibility of sensor, etc. The sensor designer can choose which scale of contact will be emphasized based on the properties of the wearable strain sensor.

(6) As compared in table 1, the current proposed textile-structured strain sensors made by intrinsic conductive fiber have the advantages of large strain range and high sensitivity. The sensing mechanism of the proposed sensor is based on contact resistance on various scales. The format, density, and material of the contact govern the properties of the sensors. Some sensor parameters should be balanced according to real application situations. A high strain range requires a large deformation of the contacts, which in turn decrease the linearity of the sensor, especially at the maximum strain region. This needs elastic fiber together with high bending modulus fiber to help improve the linearity. High sensitivity means more contacts will be involved during the extension and recovery stages. This will limit the strain range of the sensor. This is because the change of contact number cannot remain high throughout the whole range. It is necessary to use short fibers with high extensible fabric structures. Therefore, it is necessary to balance the properties of the sensor before designing the structures and choosing the materials.

Acknowledgments

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References

[1] Brady S, Lau K T, Megill W, Wallace G G and Diamond D 2005 The development and characterisation of conducting polymeric-based sensing devices *Synth. Met.* **154** 25

[2] Yang Y L, Chuang M C, Lou S L and Wang J 2010 Thick-film textile-based amperometric sensors and biosensors *Analyst* **135** 1230

[3] Chuang M C, Windmiller J R, Santhosh P, Ramirez G V, Galik M, Chou T Y and Wang J 2010 Textile-based electrochemical sensing: effect of fabric substrate and detection of nitroaromatic explosives *Electroanalysis* **22** 2511

[4] Bonfiglio A and Rossi D D 2011 *Wearable Monitoring System* (New York: Springer)

[5] Tao X M 2001 *Smart Fibers, Fabrics and Clothing* (Cambridge, England: Woodhead Pub)

[6] Tao X M 2005 *Wearable Electronics and Photonics* (Cambridge, England: Woodhead Pub)

[7] De Rossi D, Santa A and Mazzoldi A 1999 Dressware: wearable hardware *Mater. Sci. Eng.* C **7** 31–5

[8] Kuhn H H, Kimbrell W C, Worrell G and Chen C S 1991 Properties of polypyrrole treated textile for advanced applications *ANTEC '91, Montreal, Society of Plastics Engineers, Inc. (SPE)* pp 760–4

[9] Oh K W, Park H J and Kim S H 2003 Stretchable conductive fabric for electrotherapy *J. Appl. Polym. Sci.* **88** 1225–9

[10] Xue P, Tao X M, Yu T X, Kwok K and Leung S 2004 Electro-mechanical behaviour and mechanistic analysis of fiber coated with electrically conductive polymer *Text. Res. J.* **74** 929–36

[11] Wijesiriwardana R, Mitcham K and Dias T 2004 Fiber-meshed transducers based real time wearable physiological information monitoring system *8th Int. Symp. on Wearable Computers* Manchester Univ vol 1 pp 40–7

[12] Paradiso R, Milior S P A, Smartex S R L, Loriga G and Taccini N 2005 A wearable health care system based on knitted integrated sensors *IEEE Trans. Inf. Technol. Biomed.* **9** 337–44

[13] Ferna'ndez-Valdivielso C, Matı'as I R and Arregui F J 2002 Simultaneous measurement of strain and temperature using a fiber Bragg grating and a thermochromic material *Sensors Actuators A: Phys.* **101** 107–16

[14] Ho H L, Jin W, Chan C C, Zhou Y and Wang X W 2002 A fiber Bragg grating sensor for static and dynamic measurands *Sensors Actuators A: Phys.* **96** 21–4

[15] Tao X M, Tang L Q, Du W C and Choy C L 2000 Internal strain measurement by fiber Bragg grating sensors in textile composites *Compos. Sci. Technol.* **60** 657–69

[16] Pasquale E, Lorussi S F, Mazzoldi A and De Rossi D 2003 Strain-sensing fabrics for wearable kinaesthetic-like systems *IEEE S. J.* **3** 460–7

[17] Zhang H, Tao X, Yu T and Wang S 2006 Conductive knitted fabric as large-strain gauge under high temperature *Sensors Actuators A: Phys.* **126** 129–40

[18] Zhang H and Tao X M 2013 A single-layer stitched electrotextile as flexible pressure mapping sensor *J. Text. Inst.* **103** 1151–9

[19] Zhang H and Tao X 2012 From wearable to aware: Intrinsically conductive electrotextiles for human strain/stress sensing *IEEE-EMBS Int. Conf. on Biomedical and Health Informatics (BHI)* pp 468–71

[20] Zhang H, Tao X, Yu T and Wang S 2006 A novel sensate 'string' for large-strain measurement at high temperature *Meas. Sci. Technol.* **17** 450

[21] Zhang H, Tao X, Wang S and Yu T 2005 Electro-mechanical properties of knitted fabric made from conductive multi-filament yarn under unidirectional extension *Text. Res. J.* **75** 598–606

[22] Wang J F, Long H R, Soltanian S, Servati P and Ko F 2014 Electro-mechanical properties of knitted wearable sensors: Part 2—Parametric study and experimental verification *Text. Res. J.* **84** 200–13

[23] Holm R 1967 *Electric Contacts* 4th edn (Berlin: Springer) pp 7–19