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Electromechanical analysis of length-related resistance and contact resistance of conductive knitted fabrics

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Abstract

Conductive fabrics usually exhibit two types of electrical resistance: the length-related resistance and contact resistance. The length-related resistance increases with the applied extensile force, whereas the contact resistance decreases with the contact force. The resistance of conductive knitted fabrics could be modeled by the superposition of the length-related resistance and contact resistance. Three experiments were conducted to investigate the resistance of conductive yarns: two overlapped conduct yarns and conductive knitting stitches under unidirectional extensile forces, respectively; and the corresponding empirical equations were developed. The relationship of the resistance, tensile force, fabric length and width were established. The fitting curves with high coefficient of determinations (>0.94) and low standard errors (<0.18) given by the modeling equations were achieved. Therefore, the proposed model could be used to compute the resistance of the conductive knitting fabrics under unidirectional extension.

Keywords

Electromechanical analysis model, length-related resistance, contact resistance, conductive knitted fabrics

Introduction

Textiles featured with electronic function are not a new topic but are becoming one of the major growth sectors in the recent textile industry. The wearable electronic textile, based on interactive technology, forms a new market segment resulting from the miniaturization of electronics, and new innovation for both electronic and textile industries. It is anticipated that the retail markets would be of the order of billions dollar in the next decade.[1,2] Despite the huge economic potential in electronic textiles, various aspects of resistance of conductive yarn in different conditions are being widely studied and used as an essential component of electronic textiles, but the electrical stability of these kinds of textile is still a bottleneck for this research field.[3] In conductive textiles, length-related resistance and contact resistance form the most contribution to the overall resistance. The length-related resistance is only dependent on the length of conductive yarn when the extensile force is applied along its major axis, while the contact resistance is dependent on the contact area under the extensile force.[4,5] The electromechanical properties are usually not the same in simple electronic fabrics and cannot be applied to the interactive textile directly because those applications are based on the unstable non-rigid textiles. Although the fundamental electronic theories are valid for electronic textiles, the explanations of those properties are far complicated than a usual electronic circuit. The change of resistance is one of the complicated research topics in the field of wearable electronic textiles. Several authors have described experiments on the different aspects of conductive fabrics in terms of sheet resistance, electromechanism, and resistive network models etc. to explore the resistance

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problems of conductive fabric.[6–11] The relationships between the electrical resistance and load have been revealed by some papers with experimental results, it was found that the contact resistant accounts for the changes of the resistance under loading or extending.[12–14] A theoretical analysis and experimental investigations suggest that equations could accurately model the equivalent electrical resistance of jersey conductive stitches of knitwear.[5] Few studies can give some explanations for the underlying principle between the electrical resistance and load of conductive textile. Therefore, fundamental research of electronic textiles is essential for the future development.

In this paper, an overview of electromechanical properties of conductive yarns and conductive knitting stitches are given in terms of length-related resistance and contact resistance. Three experiments were conducted to investigate the equivalent resistance of conductive yarns, two overlapped conductive yarns and conductive knitted fabrics, respectively under unidirectional extensile force; and the corresponding empirical equations are established.

Theoretical

Electrical resistance of conductor

Provided by the Ohm's law, the electrical resistance, R, of the conductor is governed by equation (1), which depends on its length, L (m), cross-sectional area, A (m^2), and the resistivity, ρ (Ωm^{-1}), of the conductor.

$$R = \rho \frac{L}{A} \tag{1}$$

For coated conductive materials,[15] the effective area is modified by a multiplicative exponent constant, k, and equation (1) becomes:

$$R = \rho \frac{L}{A^k} \tag{2}$$

Given that the intrinsic resistivity and scaling factor were unchanged, the resistance is linearly proportional to the length, L, of the conductor and that is inversely proportional to the cross-sectional area A. Most of the conductive yarns belong to this category.

Contact resistance

According to the contact resistance theory,[16] the factors which determine the contact resistance, are shown in equation (3):

$$R_c = \frac{\rho}{2}\sqrt{\frac{\pi H}{nP}} \tag{3}$$

where ρ (Ωm^{-1}), H (Nm^{-2}), n and P (N) are the electrical resistivity, material hardness, number of contact points and contact pressure between the conductive yarns, respectively. The material hardness and the electrical resistivity are constants that depend on the material properties. The contact resistance is therefore inversely proportional to the number of contact points and the contact pressure.

With consideration of the unidirectional extension of the conductive knitted fabrics, the computation of the total equivalent resistance becomes more complicated due to the extension of the conductive yarns and string of the knitted loops. The resistance could be decomposed into the length-related resistance, R_l, and contact resistance, R_c. The conductive yarn consists of length-related resistance, whereas the two overlapped yarns and conductive knitted fabrics contain both length-related resistance and contact resistance.

Extension mechanism of conductive yarn

The length-related resistance, R_l, is no longer linearly proportional to the length of the yarn under the stress, because the cross-sectional area A is decreasing during the increasing of length L. Consequently, the length and the cross-sectional area of the conductive yarn are functions of tensile force, F. Equation (2) can be rewritten to reflect the factor of the tensile force, F (N), and to explicitly show the initial length, L_0, as follows:

$$R_l = f(F, L_0) = \rho \frac{L(F, L_0)}{A(F, L_0)^k} \tag{4}$$

Indeed, the length-related resistance is non-linearly dependent on the extensile force and the initial yarn length. The following modeling equation is applied to take account of the *Nth* order effect and cross-correlation between the yarn length and extensile force to the resulted resistance.

$$R_l = \sum_{n=0}^{N}\sum_{m=0}^{N} C_{mn} F^n L_0^m \tag{5}$$

where C_{mn} are the coefficients that are to be determined in the experiment.

Extension mechanism of overlapped conductive yarn

The contact resistance of the conductive yarns is stemmed from the contact pressure of the two conductive yarns and the twist of the conductive yarns, which causes torsion of the straight and parallel fibers in the yarn axis direction. However, the contact resistance caused by the twist of the conductive yarns is decreasing with the increase of the yarn or fabric length. The relationship between the tensile force, F, and the contact pressure, P, is related by the following equation:

$$P = P_0 + a_0 F \quad (6)$$

where P_0 and a_0 are the initial contact pressure in nature relaxation and a constant coefficient, respectively. As the contact resistance, R_c, is inversely proportional to the contact pressure, P, by equation (3), the equation becomes:

$$R_c \propto \frac{1}{\sqrt{P}} = \frac{1}{\sqrt{P_0 + a_0 F}} = g(F) \quad (7)$$

However, a multiplicative exponent to P is required to reflect the resistance arising from the twist of yarns. The modeling equation for contact resistance was assumed:

$$R_c = \frac{a_1}{P_0 + a_0 F} \quad (8)$$

Equation (5) is combined with equation (8) to take into account the tail resistance of the overlapped yarn. Therefore, the equivalent resistance on overlapped conductive yarn is given by the following equation:

$$R(F, L_0) = f(F, L_0) + g(F) = \sum_{n=0}^{N} \sum_{m=0}^{N} C_{mn} F^n L_0^m + \frac{a_1}{P_0 + a_0 F} \quad (9)$$

Equation (9) implies that the contact resistance plays a significant role in the initial tensile process that leads to a decrease of the total resistance when the tensile force is small; while the length-related resistance dominates the total resistance for further extension. These constants will be determined in the experiment.

Extension mechanism of conductive knitted fabric

The extension mechanism on the resistance of conductive knitted fabric by unidirectional tensile force is more complex than that of the overlapped conductive yarn. A knit loop consists of a needle loop, which is composed of a head and two side limbs and a sinker loop in the natural state illustrated in Figure 1(a). During the course of unidirectional tension of conductive fabric, the tensile force is counteracting with the friction force, which exists in the contact point between the loops and leads to the movement of the contact point. Consequently, the bending curvature of the yarn is changed. Moreover, the length of limbs, head and sinker loop may change owing to the movement of the contact point. When the tensile force further increases, the extent of the movement of the contact point is restricted and the contact pressure between head and sinker loop ascends rapidly. Meanwhile, the yarn is extended under the large tensile force as shown in Figure 1(b). Finally, the knitted fabric will break when the tensile force exceeds the breaking force of the yarn.[17]

Similarly, the resistance of a conductive knitted fabric along the wales direction could be modeled by superposition of the length-related resistance and contact resistance with the fabric length, L. Because the resistance is inversely proportional to the total number of conductive yarn wale,[11] equation (9) could be rewritten as follows:

$$R_f(F, L, W) = \frac{1}{W} \left(\sum_{n=0}^{N} \sum_{m=0}^{N} C_{mn} F^n L^m + \frac{a_1}{P_0 + a_0 F} \right) + W \cdot b_0 \quad (10)$$

where b_0 is an offset coefficient to account for the terminal resistance between the connector and the fabric under test. W is the total number of conductive yarn wale of knitted fabric.

Experimental setup

Three experiments were conducted as shown in Figure 2 to investigate the relationship between the electrical resistances and unidirectional tensile force. The length-related resistance of conductive yarns, contact resistance of two overlapped yarns, and equivalent resistance of conductive knitting stitches under unidirectional extension were examined in experiment 1, experiment 2 and experiment 3, accordingly.

Materials used

The conductive silver coating yarn (Statex Production & Distribution plc.), whose core is consisted of polyamide multifilament, was employed for this investigation. The specifications of the conductive yarn are tabulated in Table 1. The corresponding magnified image and SEM analysis are illustrated in Figure 3 and Figure 4, respectively. Cotton yarn of linear density 58tex and conductive silver coating yarn were used to knit intarsia stitch on a 12G flat knitting machine. The knitting parameters are shown in Table 2.

Experiment procedure

The experimental setup is shown in Figure 5. The copper plates were used to clamp both ends of the test sample, where a digital multimeter (Keithley) was connected to measure the resistances, which were saved to the computer in real time. The resistances of the conductive yarns and fabrics were measured, while the sample was stretched by the unidirectional extensile force produced by the Instron Universal Material

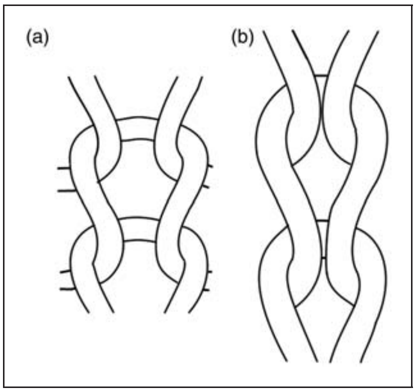

Figure 1. Change of the loop shape of a knit loop under (a) natural state and (b) extension.

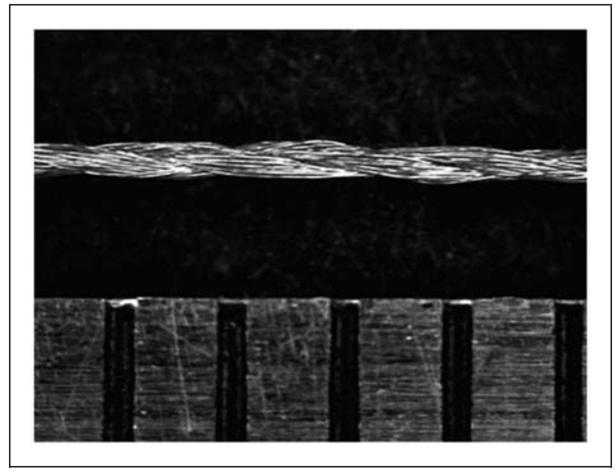

Figure 3. Magnified image of the conductive yarn B.

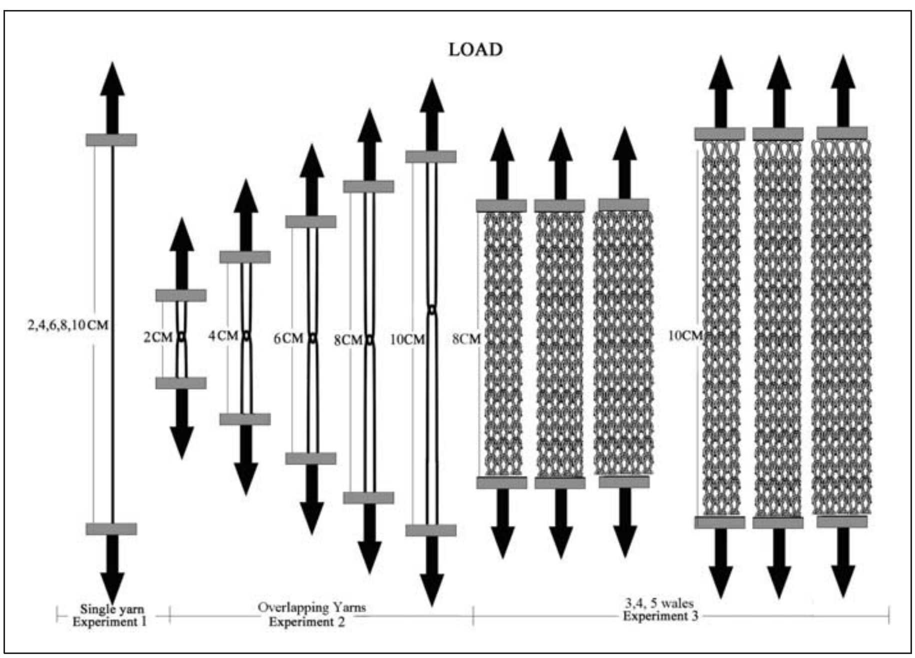

Figure 2. Setup of experiment 1, experiment 2 and experiment 3 to investigate the relationship between the electrical resistances and uni-directional tensile force.

Table 1. Parameters of conductive yarn

Diameter (mm)	Linear density (Nm)	Breaking tenacity (cN/tex)	Breaking elongation (%)	Twist (no./m)	Filaments (no.)	Conductivity (Ω.cm^{-1})
0.295	$20^s/2$	22	23.5	400	75	1–2

Tester 5944. A pneumatic clamp was employed in this experiment. The clamping pressure was 50 N. The excitation voltage was set at 2 V and the reference resistance value was 10 Ω. The measurements are related as shown in the following equation (11):

$$R_{sen} = \frac{R_{ref} v}{V_e - v} \tag{11}$$

where R_{sen} (Ω) is the measured resistance, R_{ref} (Ω) is the reference resistance, V_e (V) is the excitation voltage, v (V) is the measured voltage in the extension process

Experiment 1: length-related resistance-tensile force relationship of a conductive yarn

Extensile force produced by a constant crosshead speed of 10 mm/min was used to stretch the yarns in its longitudinal direction. The yarns, which original lengths are 2, 4, 6, 8 and 10 cm, respectively, were stretched until breaking. Five samples of each conductive yarn were tested. To prevent sliding of the yarns, knots were made at both ends of the yarns where the clampers were held.

Experiment 2: contact resistance-tensile force of two overlapped conductive yarns

The overlapped yarn was made by overlapping the two conductive yarns. Overlapped yarns with different tail lengths were held by copper plates as shown in Figure 6 were measured. They were in contact loosely in the natural configuration to imitate the actual situation in clothing. In order to eliminate the effect of loading speed, the samples with 2, 4, 6, 8 and 10 cm tail length were stretched longitudinally by an extensile force produced by a constant crosshead speed of 10 mm/min.

Experiment 3: resistance-tensile force of conductive knitted fabrics

The experiment setup was the same as experiment 1 and 2 as shown in Figure 2. The equivalent resistances of fabrics knitted by conductive yarns were measured. Two normal cotton wales remained on the two sides of conductive wales to reduce the experimental error. Three samples of the fabrics for conductive wales of 3, 4 and 5, were tested accordingly for fabric length of 8 cm and 10 cm. Extensile force produced by a constant crosshead speed of 30 mm/min was used to stretch the fabric in its wale direction which contains conductive yarn. The fabric samples were stretching until the strain reached 25 N.

Results and discussion

Experiment 1: length-related resistance-tensile force of a conductive yarn

The averaged length-related resistances vary with the tensile forces for initial yarn lengths of 2, 4, 6, 8 and 10 cm, and the corresponding fitting curves from equation (5), as shown in Figure 7. The resistance is increasing, non-linearly, with the applied tensile force and initial yarn length during the tension process. The coefficient of determination is greater than 0.98 and the standard fit error is smaller than 0.43 for N = 3. The empirical modeling equation becomes:

$$\begin{aligned} R_l(F, L_o) = {} & -1.96571 \times 10^{-4} F^3 + 6.46354 \times 10^{-3} F^2 \\ & - 5.52217 \times 10^{-2} F - 1.88988 \times 10^{-3} L_o^3 \\ & + 1.01099 \times 10^{-2} L_o^2 + 0.556491 L_o \\ & + 5.30765 \times 10^{-2} F L_o + 2.53778 \times 10^{-3} F L_o^2 \\ & - 5.77369 \times 10^{-4} F^2 L_o \\ & + 2.09058 \end{aligned} \tag{12}$$

The equation shows a high non-linear effect from the extensile force and the initial yarn lengths to the length-related resistance, as well as the cross-correlation between the force and the yarn length. Also, the high-order coefficients (N > 3) become negligible so that it could be omitted in the modeling equation. Therefore, N = 3 could achieve high accuracy for the computation.

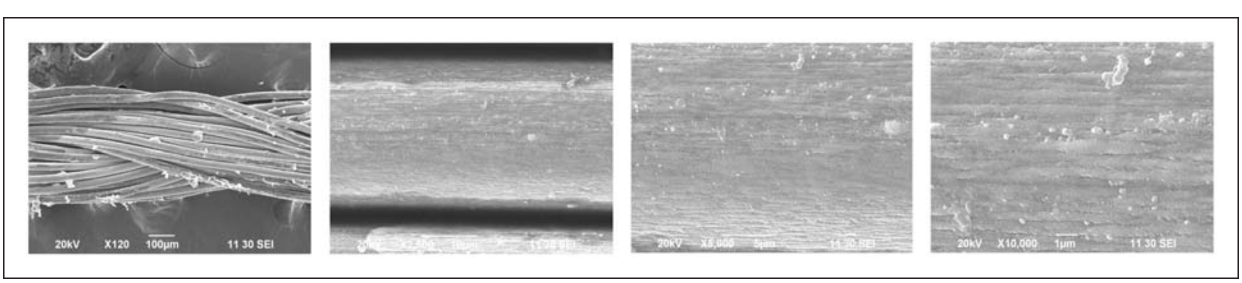

Figure 4. Scanning electron microscope (SEM) analysis of conductive yarn B at magnification factors of 120 ×, 2500 ×, 5000 ×, and 10,000 × from left to right.

Once yarn length is known, the length resistance could be computed from equation (12) with different extensile force.

When compared with the initial portion of the curve, especially the yarn length of 6, 8, and 10 cm in Figure 7, the resistances are shown to slowly decrease in the initial tension process. The resistance of the conductive yarn slowly decreases in the initial tension process due to the twist of conductive yarns that causes contact resistance between fibers in the conductive yarn and non-linearity behavior of the conductive yarn under stressing. In other words, the straight conductive yarn also exhibits length-related resistance and subtle contact resistance. However, the length-related resistance is the major resistance when the extensile force is large.

Experiment 2: contact resistance of two overlapped conductive yarns

In the experiment, two overlapping conductive yarns with the minimum tail length were employed to minimize the length-related resistance so as to determine the contact resistance and its physical insights to the total resistance. The total resistance could be thought of superposition of two factors: length-related resistance and contact resistance. The relationship between total resistance and tensile force is shown in Figure 8 for different tail lengths. The contact resistance dominates the total resistance at the initial stressing, as indicated by a little drop of the curve, whereas the length-related resistance determines the total resistance for further increasing the stress reflected by the rear portion of the curve. Because the contact resistance (equation (8)) and length-related resistance (equation (5)) are decreasing and increasing, to the tensile force respectively, together they form two competing factors as

Table 2. Knitting parameters of conductive fabrics

Knitting structure	Wale density (no./5 cm)	Course density (no./5 cm)	Loop length (mm)	Thickness (mm)
Intarsia knit	49	37	6.2	1.30

Figure 6. Experiment 2: Contact resistance of two overlapped conductive yarns with different tail lengths.

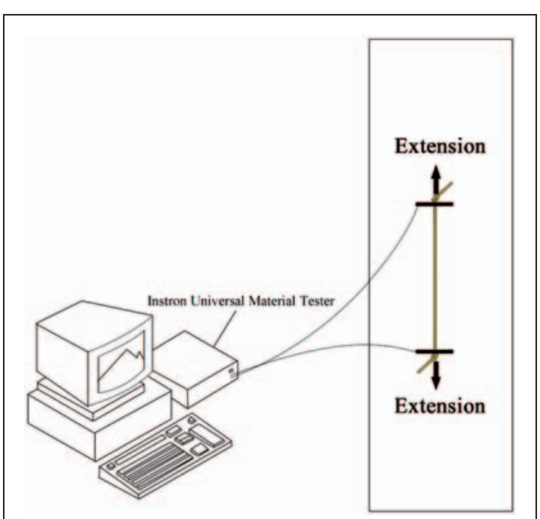

Figure 5. Experimental setup for electromechanical analysis. Test samples were clamped by the copper plates whose ends were connected to Instron Universal material Tester.

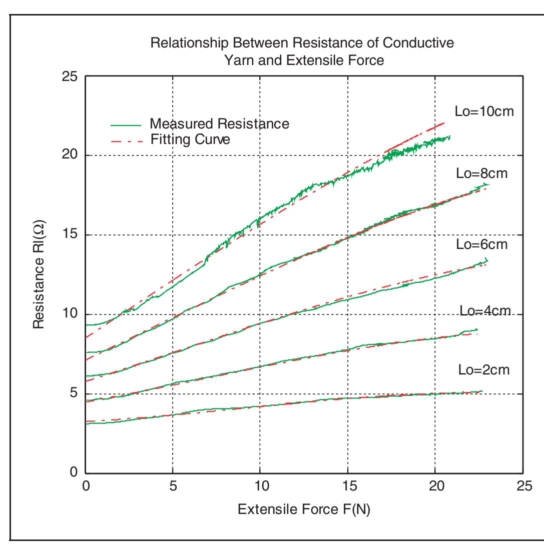

Figure 7. Relationship between the resistance and tensile force of the single conductive yarns with different lengths.

given by equation (9) and the corresponding empirical equation is shown as following:

$$\begin{aligned} R_c(F, L_o) = {} & 4.26881 \times 10^{-5}F^3 - 5.10381 \times 10^{-3}F^2 \\ & + 0.18457F - 9.24952 \times 10^{-4}L_o^3 \\ & + 1.10266 \times 10^{-2}L_o^2 + 0.343429L_o \\ & + 1.83299 \times 10^{-2}FL_o + 2.08693 \times 10^{-5}FL_o^2 \\ & + 4.95296 \times 10^{-6}F^2L_o - 1.28405 \\ & + \frac{1}{0.3121 + 3.88 \times 10^{-2}F} \end{aligned} \tag{13}$$

The coefficient of determination is greater than 0.96 and the standard fit error is smaller than 0.077 for N = 3. The modeling error is due to the assumption that the total resistance of two overlapped yarns consists of length-related resistance and contact resistance in which the contact resistance of the twisted conductive fibers of the yarns is omitted. Also, the measurement errors, the imperfection of conductive yarn, yarn surface defect and metal fatigue during stretching may cause the errors.[18]

The stationary points are found at a tensile force of 1 N as shown in Figure 9, where the rate of decrease of the contact resistance is equal to the increased rate of the length resistance. As compared the rear portion of Figure 7, the resistances in Figure 8 are almost half of that in Figure 7, because two conductive yarns of two overlapped loops were connected in parallel. Also, the contact resistance has little effect on the total resistance when the extensile force is large. The total resistance could be approximately represented by the rear portion of the curves.

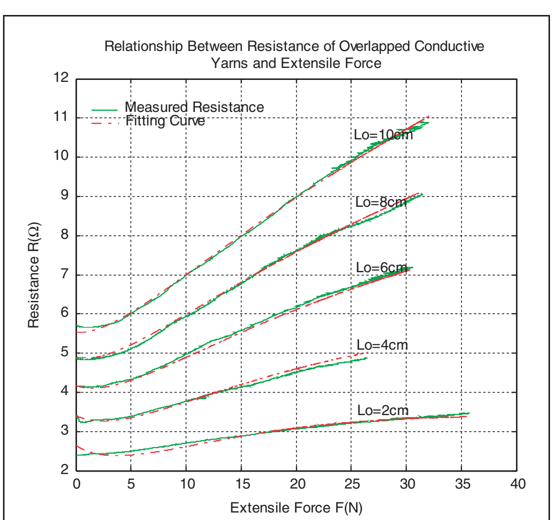

Figure 8. Relationships between total resistance and tensile force of two overlapped yarns with different tail lengths.

Experiment 3: resistance-tensile force of conductive knitted fabrics

The measured resistance and the fitting curves of the conductive knitted fabrics under unidirectional extensile force are shown in Figure 10. At the initial stretching, the fabric resistances suddenly drop due to the decreasing contact resistance and then rise because it is counteracted by the increasing length-related resistance when the force is further increasing. The obtained coefficients of determination were 0.9675, 0.9720, 0.9480, 0.9678, 0.9616 and 0.9700

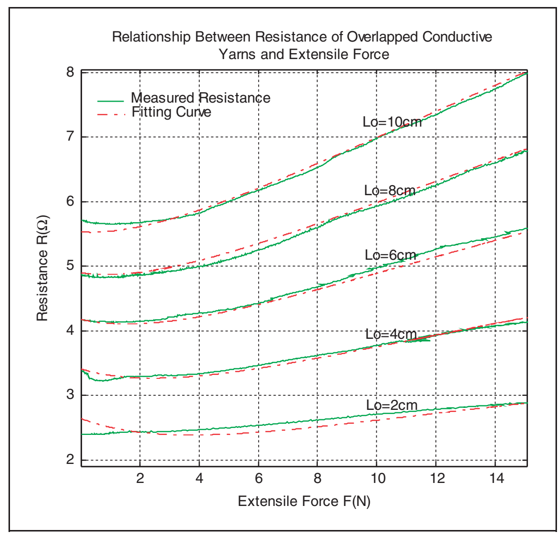

Figure 9. Relationship between total resistance and tensile force of two overlapped yarns in the initial stretching process.

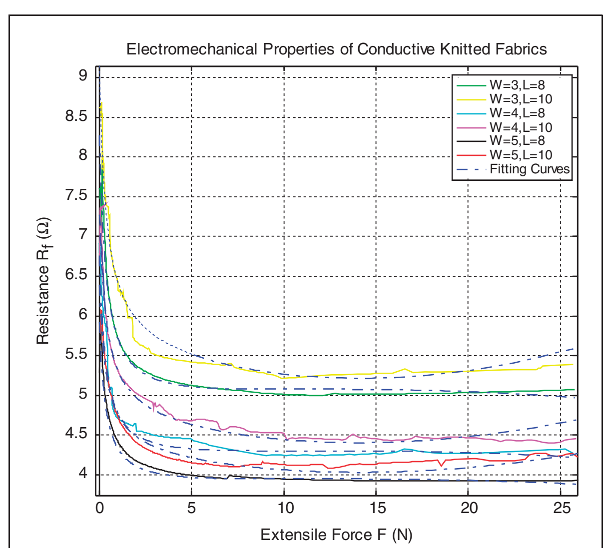

Figure 10. Electromechanical property of the conductive knitted fabrics for different number of wales and fabric lengths.

for $(W, L) = \{(3,8), (3,10), (4,8), (4,10), (5,8), (5,10)\}$, respectively. The coefficient of determination is greater than 0.945 and the standard fit error is smaller than 0.18 for $N = 2$. The experiment result implies that the resistance of the conductive knitted fabrics could be modeled by the superposition of the length-related resistance and the contact resistance. The empirical equation is obtained as follows:

$$R_f(F, L) = \frac{1}{W}\Big(-9.2717 \times 10^{-2}F^2 + 2.87112F - 4.39874 \times 10^{-2}L^2 + 1.43278L - 0.187534FL. + 2.45515 \times 10^{-3}FL^2 + 5.16357 \times 10^{-3}F^2L - 5.34228 + \frac{1}{9.21179 \times 10^{-2} + 0.2593F}\Big) + 0.281576W \tag{14}$$

The high-order effects become insignificant when the fabric dimension is high because of averaging out of the imperfections of non-rigid nature of knitted fabrics, therefore the coefficients of the order $N > 2$ could be negligible from the model equation. The standard fit errors are largely due to the measurement errors, boundary effect between conductive stitches and normal stitches and deformation of knit loops, especially when the fabric dimension is small. Also, for forces larger than 25 N, it may cause irreversible surface fracture of the conductive yarns. The increase of the number of wales from 3 to 5 decreases the standard errors from 0.1315 to 0.0882 and 0.1745 to 0.0811 for fabrics length of 8 cm and 10 cm, respectively; whereas the increase of the fabric length from 8 cm to 10 cm generally reduces the standard errors from 0.1730 to 0.1260 and 0.0882 to 0.0811 for 4 and 5 wales, respectively.

Conclusion

The electromechanical properties of conductive yarns, two overlapped conductive yarns, and conductive knitted fabrics under unidirectional extension were investigated by the three experiments. The experimental results demonstrate the equivalent resistance could be modeled by superposition of length-related resistance and contact resistance. The length-related resistance and contact resistance altogether form two competing factors that determine the overall resistance. The contact resistance acts as a decreasing factor during the initial stretching process, whereas the length-related resistance dominates the total equivalent resistance for the further increasing of tensile force in the stretching process. The empirical equations were developed with high coefficient of determination (0.99, 0.96, 0.94) and low standard errors (0.43, 0.077, 0.18) of the fitting curves for experiment I, II, and III, respectively. The relationship between fabric resistances, number of wales, fabric lengths and the tensile force of the conductive knitting fabric are related by the empirical equations. The high-order parameters account for the non-linearity and high complexity of the conductive knitting structures under tensile force. The proposed model could be applied to compute the resistance of the conductive knitted fabrics under unidirectional stretching as well as to aid the industry to design conductive fabrics to meet wearable electronic applications.

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