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An Investigation of the Physical and Electrical Properties of Knitted Electrodes When Subjected to Multi-Axial Compression and Abrasion †

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Abstract: Knitted electrodes are a key component to many electronic textiles including sensing devices, such as pressure sensors and heart rate monitors; therefore, it is essential to assess the electrical performance of these knitted electrodes under different mechanical loads to understand their performance during use. The electrical properties of the electrodes could change while deforming, due to an applied load, which could occur in the uniaxial direction (while stretched) or multiaxial direction (while compressed). The properties and performance of the electrodes could also change over time when rubbed against another surface due to the frictional force and generated heat. This work investigates the behavior of a knitted electrode under different loading conditions and after multiple abrasion cycles.

Keywords: electronic textiles; E-textiles; electrode; tensile testing; abrasion

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1. Introduction

Electronic textiles (E-textiles) can be fabricated using a number of methods [1], with a popular technique being to create electrical interconnections and electrodes by knitting or weaving conductive yarns. Electrodes made using this method can be employed as a component in a number of different sensing systems including pressure sensors [2] and for electrocardiogram measurements [3]. This method produces E-textiles with good textile properties (i.e., drape, breathability, etc.); however, the functionality of this type of electrode under multiaxial loading and after repeated abrasion appears to be absent in the literature.

In this work, knitted electrode samples were produced and their physical and electrical properties were tested under uniaxial stretching, multiaxial compression, and after multiple abrasion cycles to better understand how they might perform during use and after excessive use. The electrode design chosen was similar to a design previously used to create a heart rate monitoring seat back [3].

2. Materials and Methods

2.1. Knitted Electrodes

Rectangular electrodes (6 cm × 4 cm; see Figure 1) were produced on a computerized flat-bed knitting machine (Stoll ADF 3 E14; Stoll, Reutlingen, Germany) using an intarsia knitting technique. The electrodes formed part of the top layer of a knitted spacer structure, which used an interlock structure behind the electrode. The conductive elements were manufactured using silver-plated, multifilament, polyamide yarn (part number 20012223534HCB; Shieldex®, Statex GmbH, Bremen, Germany); the non-conductive basefabric was created using cotton (count = NE 24/3; Yeoman Yarns, Leicester, UK) and polyester yarns were used for the spacer material (164 dtex, 48 filaments; J.H. Ashworth and Son Ltd., Hyde, UK).

Figure 1. Photograph of the knitted electrode.

2.2. Uniaxial Stretching Testing Procedure

Uniaxial loading tests were conducted on the knitted spacer electrode using a zwickiLine tensile testing machine (Z2.5; Zwick/Roell, Ulm, Germany) following a modified version of BS EN 14704-1:2005 (Determination of the elasticity of fabrics. Strip tests). Resistance was measured using a custom Wheatstone bridge fed into a voltage input on the zwickiLine tensile testing machine for this procedure, the samples underwent six loading-unloading cycles at a strain of up to 20%. To study the force degradation and monitor the resistance changes when stretched over time, at the 6th cycle, the samples were held at their maximum strain percentage for 60 s. Results were measured for five electrode samples.

2.3. Multiaxial Compression Testing Procedure

Multiaxial loading tests were carried out on knitted spacer electrodes using the zwickiLine tensile testing machine according to BS EN 14704-2:2007 (Determination of the elasticity of fabrics. Multiaxial tests); resistance was measured throughout as described above. Samples were cut according to the dimensions of the multiaxial test rig (diameter = 120 mm) with the knitted electrode positioned at the center point. A hemispherical probe (diameter = 100 mm) was used to compress the samples. Samples underwent six cycles of loading-unloading up to 10 N, followed by an additional two cycles while increasing the force to 20 N and 30 N (respectively). The knitted electrodes were held for 900 s while under 10 N, 20 N, and 30 N loading to monitor the force degradation and the variation in the resistance. Results were measured for five electrode samples.

2.4. Abrasion Testing

The Martindale Abrasion Tester (902 Mini Martindale; James Heal Ltd., Halifax, UK) which complies with ISO 12947 ISO 12947-1:1998 (Textiles—Determination of the abrasion resistance of fabrics by the Martindale method—Part 1: Martindale abrasion testing apparatus) was adapted to conduct the abrasion test using abrasive fabric. The knitted electrode samples were mounted on the holding area while abrasive material was rubbed over the knitted electrode (left to right) for 5000 rub cycles. Throughout the test the resistance over the electrode was measured using a the Wheatstone bridge and a data acquisition system (USB-6001; National Instruments, Austin, TX, USA), the surface temperature of the electrode was monitored using a thermal camera (FLIR I7 Thermal Imaging Camera; FLIR Systems, Wilsonville, OR, USA), and the physical appearance of the electrode was observed under a digital microscope (VHX-5000; Keyence, Osaka, Japan) to record any visible damage after every 1000 rubs.

3. Results and Discussion

3.1. Uniaxial Loading

Figure 2 shows the effect of uniaxial loading and force degradation on a single electrode. The results also show the corresponding change in electrical performance.

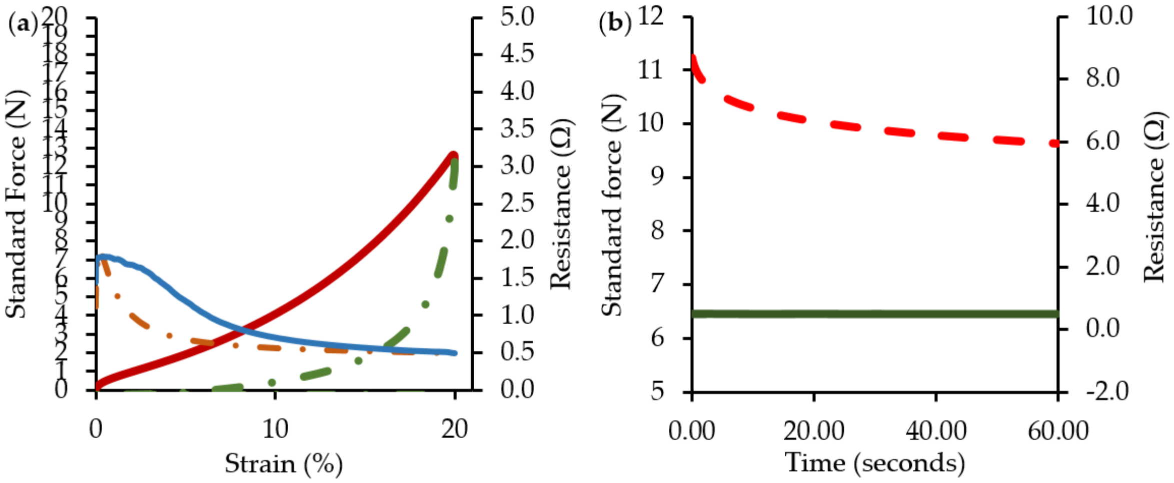

Figure 2. (**a**) Uniaxial tensile tests on a single knitted spacer electrode. Results are the average of five loading and unloading curves. The standard force (red and green lines) and resistance (blue and orange line) are both shown. Loading is shown with a solid line, and for unloading a dotted line was used. (**b**) Force degradation of the electrode when held at 20% strain for 60 s. Force presented by the red dotted line, with resistance shown by the green line.

The results for the uniaxial tensile test (Figure 2a) showed a sudden increase in resistance during the loading, followed by a substantial drop in resistance. An increase in resistance followed by a decrease was observed while unloading the sample. This increase within the first section of the cycle (0% to 5%) could be attributed to a reduction in contract points between the yarns while the structure relaxed. Over time, the yarns would relax re-establishing a greater number of contact points. This behavior was observed for all five electrodes tested and is in agreement with tensile tests on this type of electrode previously presented in the literature [3]. The force degradation experiment (Figure 2b) showed a force degradation of 1.6 N after 60 s, however resistance remained constant throughout.

3.2. Multiaxial Loading

Force degradation and corresponding electrical resistance measurements for electrodes subjected to multiaxial loading are shown in Figure 3.

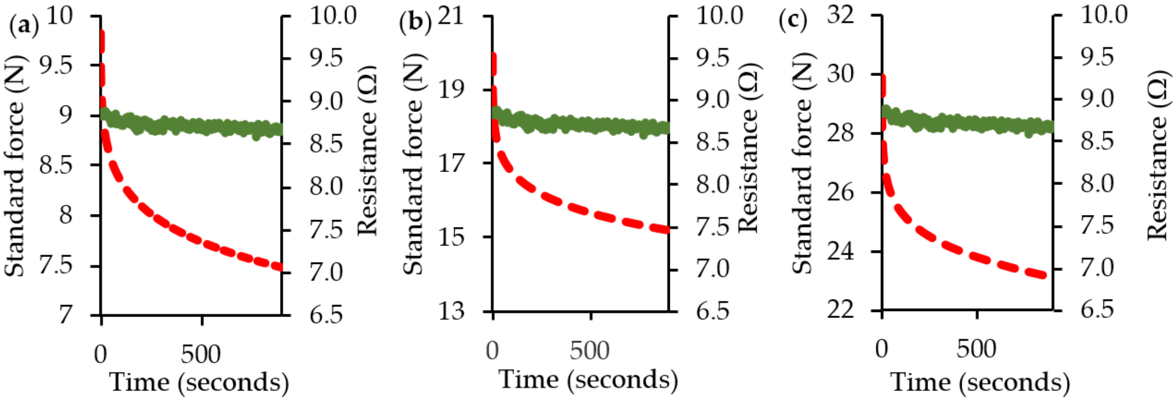

Figure 3. Force degradation (presented as a red dotted line) and electrical resistance (presented as a green line) as a function of time for electrodes undergoing multiaxial loading. (**a**) 10 N loading force. (**b**) 20 N loading force. (**c**) 30 N loading force.

Force degradations of 2.34 N, 4.69 N, and 6.77 N were observed for loading forces of 10 N, 20 N, and 30 N, respectively. The results for the multiaxial loading tests showed that despite force degradation, the electrical resistance was stable during the test period of 15 min for all three applied forces (10 N, 20 N, and 30 N). These outcomes confirmed that the knitted electrodes were unlikely to deform significantly during normal use and that these deformations would not affect the electrical properties of the electrode significantly.

3.3. Abrasion Testing

Figure 4a,b shows the resistance of the electrode as a function of rub number. Figure 4c shows the surface of the electrode after 5000 rubs.

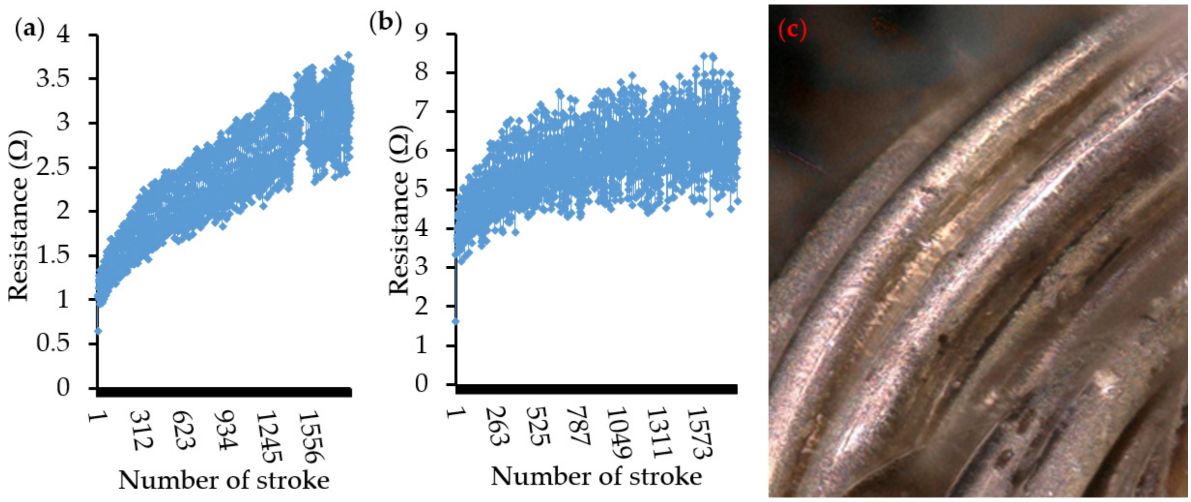

Figure 4. Resistance as a function of stroke number. (**a**) Rub 0–1000 Rub (1837 stroke). The surface temperature rose by 4.2 °C during these experiments. (**b**) Rub 4000–5000 Rub (1821 stroke). The surface temperature rose by 5.4 °C for these experiments. (**c**) Microscope image of the surface fibers after 5000 rubs.

It was observed that by increasing the number of rub cycles, the electrical resistance did increase. Resistance increased by a factor of three after 1000 cycles, which would be significant for some sensor systems. These increases may be due to the breakages of the conductive fibers, stripping of the conductive coating, or a rise in the temperature during the test procedure. A temperature increase of around 4–6 °C was observed after 1000 rubs due to friction. It is believed that this increase in resistance was not exclusively due to a temperature increase as the electrodes initial resistance (~1 Ω) had risen to close to 8 Ω for some of the measurements shown in Figure 4b. The microscope image of the surface fibers (Figure 4c) also shows that some of the conductive silver plating had been lost after 5000 rubs.

4. Conclusions

This work investigated the physical and electrical properties of knitted textile electrodes. During uniaxial testing, it was observed that while the electrode stretched, the resistance over the electrode raised and then starting to descend. This effect was believed to be due to an increase or decrease in the number of contact points between the conductive threads throughout the procedure. It was noted that when the electrode stayed stretched at a defined strain percentage for the evaluation of force-degradation, the resistance remained constant. This stable behavior would be a useful characteristic for many sensing applications. When subjected to a multiaxial load, the electrical resistance was also seen to remain stable. Performing abrasion testing showed a significant increase in the resistance over the electrode after 5000 rubs. Abrasion testing highlighted the significance of structural deformation, materials deteriorating, and the importance of temperature on the resistance. This would affect the output signals produced by textile electrodes for some applications.

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