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A Knitted Multi-Junction Pressure Sensor That Uses Electrical Resistance to Determine the Applied Pressure: Development and Characterization †

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† Presented at the International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles (E-Textiles 2019), London, UK, 12 November 2019.

Published: 4 December 2019

Abstract: The measurement of pressure at the skin is highly important for a number of human-based monitoring applications. This work presents a resistive knitted spacer pressure sensor for monitoring the pressure at the skin–clothing–seat interface for wheelchair users. The sensor has been characterized over a relevant range of pressures, and its hysteretic behavior has been analyzed. Preliminary work towards creating supporting hardware for recording pressure at multiple junctions across the sensor has been presented.

Keywords: electronic textiles; e-textiles; health monitoring; pressure

1. Introduction

Pressure at the skin interface is a critical parameter to monitor in a variety of medical and health monitoring applications. This can range from pressure ulcer prevention [1] to analysis of breathing patterns [2]. In many cases the sensor will be in direct contact with the skin making comfort critical, and as a result the use of textiles as a substrate for pressure sensing has received significant attention over the past two decades [3]. Many fully textile pressure sensors described in the literature use a capacitive interlayer [4,5] which requires expensive and complex hardware to accurately measure capacitance from multiple junctions across the sensor.

This work focused on designing a system suitable for monitoring pressure profiles exerted on a seat by a wheelchair user, as the prolonged application of pressure is known to lead to the formation of ulcers, and frequent repositioning is required. A comfortable system that can take point–pressure measurements over the seat's surface can provide a warning to the user that they need to reposition if pressure has been applied to one point for too long.

This study focused on the engineering of a novel pressure-sensing textile based on a knitted spacer structure that used a resistive interlayer. The pressure sensor was created using a computerized flat-bed knitting machine in a single production step, with the general structure being similar to a capacitive knitted spacer pressure sensor design previously described in the literature [6].

A small resistive knitted spacer pressure sensor was produced and the performance of a single junction with different applied forces and areas of applied force (introducing pressure changes) were explored. Hysteretic effects were also investigated for a single junction, as hysteresis is a known issue for this type of sensor [4]. These experiments were repeated using a full-sized pressure sensor designed for use as a wheelchair cover. Finally, initial experiments using a low-cost Arduino-based system for monitoring the resistance at each point across the sensor have been presented.

2. Materials and Methods

2.1. Resistive Knitted Spacer Pressure Sensor Production

Small (170 × 155 mm) and large (410 × 450 mm) resistive knitted spacer pressure sensors were produced for this work. The sensors each had 12 mm wide knitted silver electrodes (conductive yarn: 235/32 dtex–2–ply–HC +B silver yarn, Shieldex®, Bremen, Germany) that were perpendicular to one another on each of the outer fabric layers of the sensor (Figure 1). The outer layers were separated by a ~3 mm thick fibrous spacer structure, which was made from a mixture of polyester (164/48 dtex) and high-resistance conductive yarns (GL2016-031, Conductive Metal Staple Yarn, HITEK Electronic Materials, Scunthorpe, UK). Junctions were formed where an electrode on the top outer fabric and an electrode on the bottom outer fabric crossed, allowing for spatially-resolved measurements to be taken. The pressure sensors were produced using a computerized flat-bed knitting machine (ADF 3 E14; Stoll, Reutlingen, Germany).

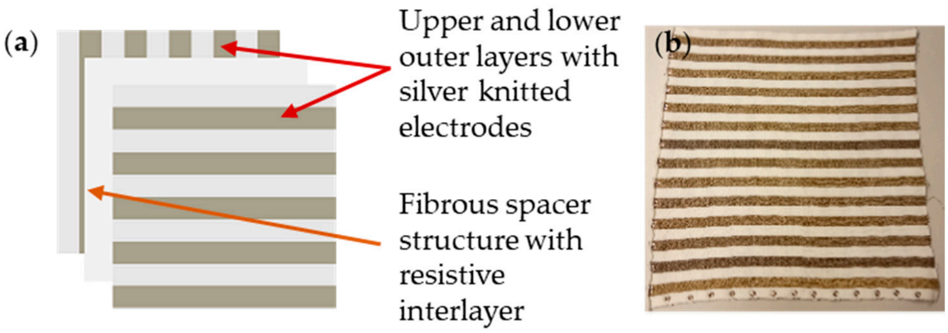

Figure 1. The resistive knitted pressure sensor. (**a**) An expanded illustration showing the three layers of the sensor: two outer fabric layers with knitted electrodes, and an inner spacer structure. (**b**) A photograph of the larger resistive knitted pressure sensor.

2.2. Characterization of Resistive Knitted Spacer Pressure Sensors

The pressure sensitivity of the sensors was examined for a single junction by exploring different applied forces over the junction, and different areas of applied force; this was important as the complex deformation of the textile spacer structure may result in different responses to pressure depending on whether pressure was changed with force or applied area [7]. Pressure changes were induced using round acrylic disks (diameter 15–70 mm) and metal weights (0.1–3.0 kg). Fixed force experiments investigated pressures of 2.5–55.5 kPa, and the fix area experiments covered pressures of 1.4–41.6 kPa. For hysteresis experiments a fixed area (30.0 mm diameter round disk) was used with the applied weight increased, and then decreased, covering a pressure range of 0–36.1 kPa. All resistance measurements were taken using a digital multi-meter (Model 34410A; Agilent Technologies UK Limited, Stockport, UK) unless otherwise stated. All reported values are the average of four repeat measurements using a single sample. All graphs were prepared using either IGOR Pro (Version 7.0.2.2; Wavemetrics, Lake Oswego, OR, USA) or Matplotlib [7].

2.3. Supporting Electronics and Processing of Data from Multiple Junctions

A supporting hardware unit was prepared to record data from the multiple junctions on the sensor. In the first instance this solution logged the data for future analysis. The system comprised of an Arduino Mega (Arduino LLC, Boston, MA, USA) and a bespoke circuit board, which was attached to the sensor; resistance measurements were taken using a voltage divider circuit. The Arduino was used to send 3 V through one electrode (via a transistor and a benchtop power supply), and then record the voltage over an electrode on the other side of the sensor. By addressing each of the electrodes, a full map of the sensor's 144 junctions could be generated. Data were collected using a combination of the Arduino IDE (v1.6.9) and Python (v2.7.12; Python Software Foundation, Wilmington, DE, USA) software running bespoke scripts. The authors would like to note that at the time of writing most of the junctions could be successfully addressed, and work on the supporting hardware and software is ongoing.

3. Results

3.1. Resistive Knitted Spacer Pressure Sensor Characterization

The pressure sensitivity and hysteric behavior of the small resistive knitted spacer pressure sensor was investigated, as shown in Figure 2.

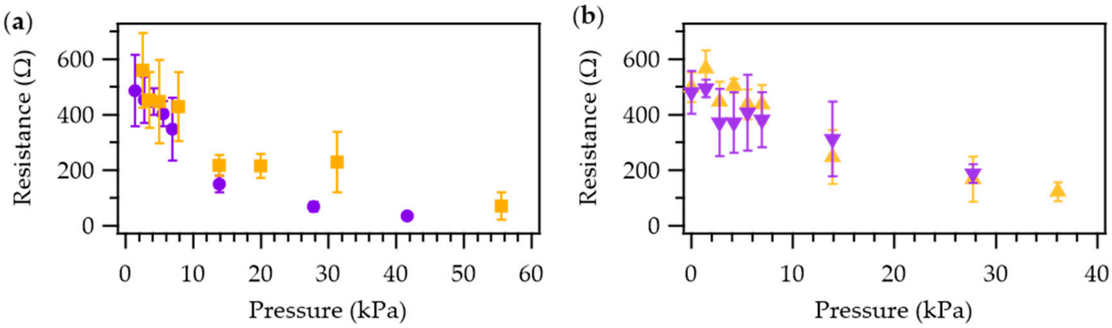

Figure 2. Characterization of the small resistive knitted spacer pressure sensor. All datapoints present the average of four measurements, with the standard deviation shown by the error bars. (**a**) Sensor response to changes in pressure where the force (●) and the area of applied force (■) were used to change the applied pressure. (**b**) Analysis of the hysteresis experienced by the sensor showing an increase (▲) and decrease (▼) in the applied pressure.

Figure 2a clearly shows that the small resistive knitted spacer pressure sensor was pressure sensitive over the range of pressures explored, and that applying pressure through increased force or area of the applied force did not affect the sensors response. Figure 2b showed that for a single junction the sensor response was not different if pressure was being applied or removed for the relevant range of pressures. The correct function of this small sensor led to the construction of a large resistive knitted spacer pressure sensor, and characterization was repeated for this sensor (Figure 3).

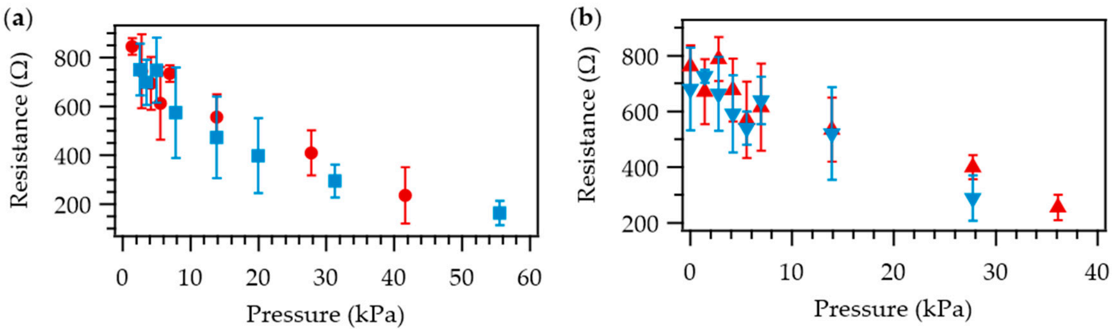

Figure 3. Characterization of the large resistive knitted spacer pressure sensor. All datapoints present the average of four measurements, with the standard deviation shown by the error bars. (**a**) Sensor response to changes in pressure where the force (●) and the area of applied force (■) were used to change the applied pressure. (**b**) Analysis of the hysteresis experienced by the sensor showing an increase (▲) and decrease (▼) in the applied pressure.

The behavior of a single junction on the large resistive knitted spacer pressure sensor showed very similar behavior to its smaller counterpart, with the most notable difference being slightly higher recorded resistances.

3.2. Taking Resistance Meassurments from Multiple Junctions

The pressure sensor was connected to the bespoke supporting electronics for recording data from multiple junctions. Simple experiments saw the investigator sit on the sensor (4 min), stand (4 min), sit on the sensor (3½ min), and stand again, with the resistance for each junction recorded. The results indicated that the global hysteresis, due to large material deformations over the textile sensor, made extracting meaningful results difficult (data from a single junction are shown in Figure 4a). To overcome this a simple algorithm was developed. The algorithm applied a linear regression to the five previous data points and based on the gradient determined whether additional pressure was being applied, the pressure applied was constant, or if the pressure was being relieved. This information was used to set a binary value showing when pressure was or was not applied (Figure 4b). In a practical scenario if the 'pressure applied' condition occurred for over 15 minutes on any of the junctions, the user would be warned.

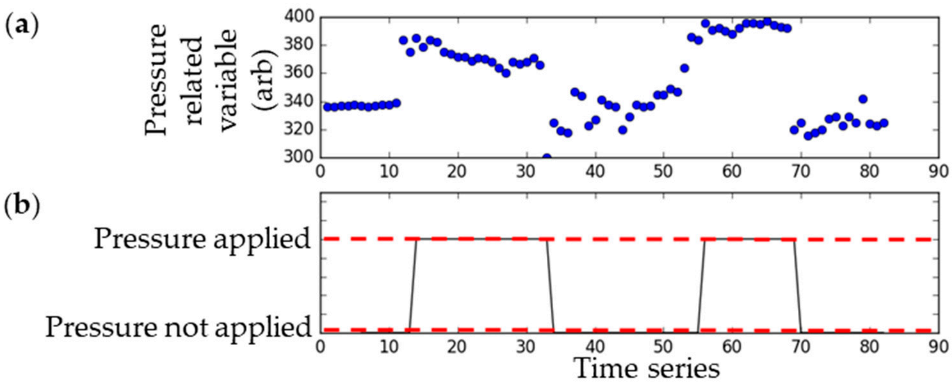

Figure 4. Results from a single junction where the investigator sat on the sensor, stood, sat again, and stood. (**a**) Raw data. (**b**) A determination of whether pressure was or was not applied.

4. Conclusions

This research has demonstrated a resistive knitted spacer pressure sensor that correctly functioned over the range of pressures of interest for a wheelchair seat cover. Preliminary work towards creating supporting hardware to operate with the sensor has been conducted, and early results have shown that the hardware/software combination can identify if pressure has been applied, removed, or held constant.

Author Contributions: Conceptualization, T.H.-R. and T.D.; methodology, T.H.-R.; software, T.H.R.; investigation, T.H.-R.; knitted sensor production, C.O.; writing—original draft preparation, T.H.-R.

Acknowledgments: The authors would like to acknowledge Nottingham Trent University for providing financial support to conduct this research.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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