Design of Knitted Pressure Sensors for Tactile Perception Applications

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***Abstract*—As an emerging technology, smart textiles attract a lot of interest in various fields in healthcare, sports, entertainment, *etc*. The new trend in smart textiles is to design sensor elements that are entirely textile-based consisting of conductive and non-conductive yarns which make the traditional sensor systems more comfortable and available for everyday use. In this study, stretchable knitted pressure sensors with different configurations and designs were produced by using commercial conductive yarns. By controlling the knit structure, the overall resistance can also be fine-tuned for practical pressure sensor applications. The impact of different knit densities and knit designs on the pressure sensing performance is investigated for tactile sensing and force distribution applications for flat-knitted and dome-like knitted sensors. Initial studies showed that the flat structures knitted less densely and in more stretcher knit designs result in better sensor performance with a sensitivity of 0.71 kPa^{-1} and within the pressure ranges of 0 to 0.71 kPa anda sensitivity of 0.13 kPa^{-1} within a pressure range of 0.70 to 2.5 kPa. This pressure sensor is knitted with the Rib 3x3 design and with a stitch length of 3 mm, and the response time of the sensor is measured as 220 msec. For dome-like pressure sensors, Rib 3x3 showed a relatively better sensitivity value within a pressure range of 0 to 10 kPa. A practical application of these sensors can be for touch detection in human-computer interaction applications.**

Keywords*—*pressure sensors*; *textile-based sensors; knitting

I. INTRODUCTION

As an emerging technology, textile-based sensors gained a lot of attention over the years due to their intrinsic softness, flexibility and comfort properties. They can distinguish between various environmental stimuli such as strain, pressure and temperature which enables them to be used in applications such as human-computer interaction [1], health monitoring applications [2], human motion recognition [3], and so on.

Textile-based pressure sensors show high-pressure sensing ability and improved flexibility when compared to traditional pressure sensors. Depending on the application area, textile pressure sensors can be tuned in to have the desired characteristics. Monitoring physiological characteristics such as speaking, aspiration and pulse require low pressure, ranging from 0 to 10 kPa. The medium pressure range (about 10-100 kPa) is suitable for the detection of finger movements like clicking a mouse button, whereas the high-pressure range (100 to 1000 kPa) can be used for pressure sensing in socks and wheelchairs [4]. In addition to the pressure range, other performance indicators are sensitivity, durability, detection range and response time [5].

Textile-based pressure sensors manufactured from commercially available materials have been studied previously by several researchers. Riley, Oliveria, Morris and Dias focused on knitted spacer pressure sensors for monitoring wheelchair users' seat posture [6]. They explored the effect of pressure, applied pressure area and hysteresis of the sensor and found out that knitted sensors could measure up to a pressure of 25 kPa. Baribina, Oks, and Eizentals studied the comparative analysis of the effect of pressure loads on knitted pressure sensors with different shapes and knitted with copper-coated acrylic yarns. They concluded that filled-shaped sensors in rectangular forms show the highest sensitivity at lower pressures [7]. Tian et al. produced a piezoresistive pressure sensor in the form of a composite pillow and noted that the sensor showed a high sensitivity of 3.5 kPa^{-1} and good durability. They also concluded that the change in diameter under pressure results in a big change in sensitivity which proves the importance of the structural design of pressure sensors [8]. Although metallic particle-coated yarns and conductive blended yarns have been used for making knitted pressure sensors [9], there is still a lack of attention on directly implementing conductive yarn into piezoresistive pressure sensors. In this study, we investigate the performance of knitted pressure sensors using commercial conductive yarns and materials. The proposed knitted pressure sensor designs possess the potential to be used in different application areas.

This paper is structured as follows: In Section I, there will be an introduction to textile-based pressure sensors, followed by an experimental section in Section II describing the material and measurement technique. Results and discussion will be summarized in Section III and the paper is finalized with the conclusion in Section IV.

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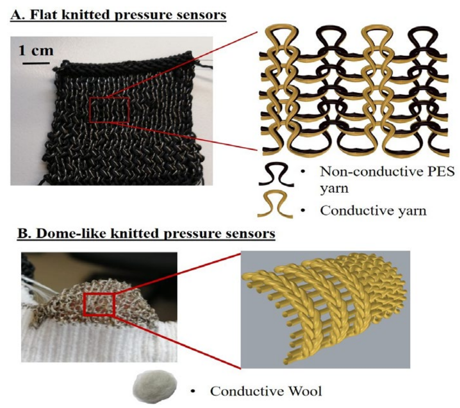

Figure 1. Knitted pressure sensors: A. Fat knitted, B, Dome-like knitted pressure sensors.

II. Experimental Section

In this section, the materials used in sensor design and the measurement technique that we used to evaluate the sensor performance will be explained respectively.

A. Materials

In this paper, we conducted a study on the electromechanical performance of knitted pressure sensors in which the material and process parameters were varied systematically. In terms of the materials, silver-plated nylon yarn from Shieldex witha resistivity of ≥600Ω/m and non-conductive PES yarn with a linear density of dtex 110/32 is used. The stitch density and the knit designs were the two parameters that we changed as knitting parameters for the pressure sensors. As shown in Fig. 1, two types of designs were produced one of which is rectangular and the other in a dome-like form. These forms were selected to investigate the importance of the structural design on sensing performance. The advantages and disadvantages of two different sensors were compared in Table I.

TABLE I. COMPARISON OF FLAT AND DOME-LIKE KNITTED PRESSURE SENSORS

A&D	**Comparison of flat and dome-like sensors**	
	Flat knitted sensor	***Dome-like sensors***
Advantages	Easy to produce at one go. Can be directly attached to the skin.	Short response time Easy to use for tactile perception applications – bump form
Disadvantages	Low detection range	Complex sensor design

Rectangular samples were knitted via plating technique in such a way conductive and non-conductive yarn were knitted together. The dimension of the flat knitted sensors is 4 x 4 cm^2. NP number and knit design were changed to examinethe sensitivity, detection range and stability performance of the samples. The NP number which refers to the number of pitch directly change the loop length and changes the fabric tightness. In dome-like structures, the sensor part was produced only by using conductive yarn. The diameter (D) of the dome-like pressure sensor is 24 mm, and its area is calculated with the formula of $S=\pi(D/2)^2$. To gather the resistance change values under deformation, conductive wool which was purchased from Bekinox® W12/8 as a filler was inserted inside and optimized. The knitted pressure sensors used in this study have been weft-knitted on a Stoll CMS 530 flat knitting machine with an E8 machine gauge and 0.30 m/ m/sec carriage speed.

B. Measurement Technique

Knitted pressure sensors were evaluated in terms of sensitivity, in which P refers to applied pressure while ΔR refers to the resistance change and R_0 is the initial resistance of the sensor.

$$S = (\Delta R/R_0)/P \tag{1}$$

Sensitivity tests were conducted for flat knitted sensors by applying the same size blocks as pressure. And for dome-like knitted pressure sensors, sensitivity tests were conducted by using a rheometer in compression mode. During the test, a digital multimeter was used to record the sensor's resistance by connecting the cables on the sensor's edges, and 2 wire resistance measurement was conducted. The test speed was set as 20 μm/sec. The axial force range is set to be between 0 and 10N.

III. Results and Discussion

In this section, the sensor performances of flat-knitted and dome-like pressure sensors will be analyzed and the results will be discussed in terms of sensitivity and detection range.

A. Analysis of flat knitted pressure sensors

Flat knitted sensors in different knit designs were evaluated in terms of sensitivity and detection range. Resistance changes were collected by loading different weights on top of the sensors and tests were conducted three times per set. Pressure sensors in the forms of Rib 1x2, 2x2 and 3x3 were knitted in different NPs of 14 and 15. As can be seen in Table II, the pressure sensitivity of the Rib 2x2 and Rib 3x3 sensors increases as the loop length increased from NP 14 to NP 15. Fabrics with high stretchability allow the creation of more pressure-sensitive sensors. [3]. In addition to that, Rib 3x3 sensors have a higher elasticity than the Rib 2x2 which can explain the better sensitivity values. Under loading, yarn-to-yarn contacts are adjusted which leads to a change in overall fabric resistance [9]. Response time is another important parameter to minimize delays during application. The Rib 3x3 design knitted with NP15 has a response time of 220 msec with a detection range of 0-0.7 kPa.

TABLE II. SENSITIVITY RESULTS OF FLAT KNITTED PRESSURE SENSORS

Knit Design	**Electromechanical Properties**		
	NP	***Sensitivity (kPa^{-1})***	***Detection Range (kPa)***
Rib 1x2	15	0.10±0.006	0-2.6
Rib 1x2	14	0.23±0.01	0-0.7
Rib 2x2	15	0.28±0.02	0-2.0
Rib 2x2	14	0.09±0.004	0-1.3
Rib 3x3	15	0.71±0.01	0-0.7
Rib 3x3	14	0.05±0.03	0-2.0

[a]Loop length.

As a preliminary study, Rib 3x3 sensors knitted with NP 15 were tested to explore whether the sensor distinguish the different pressures. Blocks of the same size corresponding to 1.2N are used to investigate the effect of pressure on resistance by applying pressure to the sensor area. As shown in Fig. 2, the Rib 3x3 flat knitted sensor has a good ability to distinguish the different loading forces.

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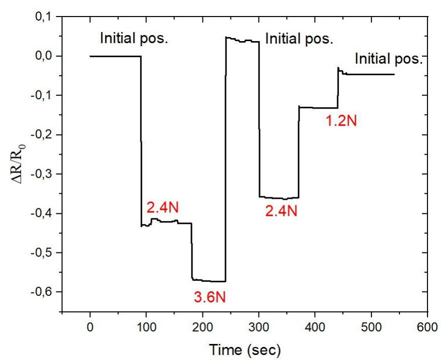

Figure 2. The response of the Rib 3x3 sensor knitted with NP15 when different pressure is loading and unloading.

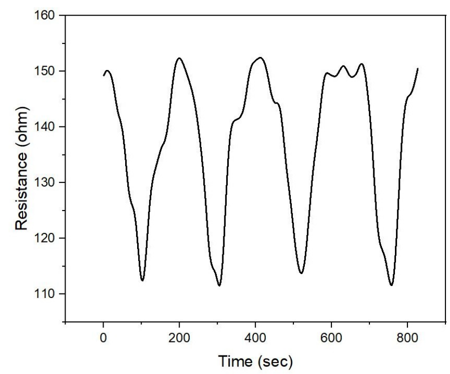

Figure 3. Cyclic test of Rib 3x3 dome-like knitted sensor

According to the preliminary results in Table II, Rib 2x2 and Rib 3x3 were chosen for the following knit design.

B. Analysis of dome-like knitted pressure sensors

In this section, dome-like knitted pressure sensors were prepared and the performance was evaluated in terms of sensitivity and detection range. Because of the difficulties in the manufacturing process, samples were not produced with higher NPs like in the flat knitted sensors and were knitted with NP 9. Rib 2x2 and Rib 3x3 samples were produced. The conductive wool amount is set as 0.046g. The results were depicted in Table III. The Rib 3x3 sensor showed better sensitivity performance than Rib 2x2 at a pressure range of 0-10 kPa.

As mentioned in Table I, the detection range of flat-knitted sensors is lower than the dome-like sensors because of the contact areas and the interfaces related to the sensor design. When we think about the tactile perception application, a higher detection range is needed to be efficiently used which makes dome-like structures more promising. And higher sensitivities were observed for flat-knitted sensors at low detection ranges with looser samples. This can be related to the diameter variation in the conductive-filled assembly fibers, sensitivity changes can be obtained [9]. For future studies, dome-like sensors will be produced in a looser form and the sensitivity range will be compared with the flat knit sensors at lower pressures.

TABLE III. SENSITIVITY RESULTS OF DOME-LIKE KNITTED PRESSURE SENSORS

Sample *Names*	**Electromechanical Properties**		
	Filler (g)	***Sensitivity (kPa^{-1})***	***Detection Range (kPa)***
Rib 3x3	0.046	0.020 ± 0.004	0-10
Rib 2x2	0.046	0.015 ± 0.001	0-10

The Rib 3x3 dome-like sensor knitted with NP 9 was further investigated to explore its performance during loading and unloading. As shown in Fig. 3, 4 cycles were applied and it demonstrates that the sensor responds to the pressure changes. The dome-like knitted sensors have much lower sensitivity than the flat knitted sensors but do react properly when activated by a light finger press.

IV. CONCLUSION

This study demonstrates the importance of the structural design of knitted pressure sensors. Two different types of knit designs were produced and their sensor performance was evaluated. In the flat knitted form, Rib 3x3 with NP 15 possesses a high sensitivity of 0.71±0.01 kPa^{-1}. Apart from flat knitted structures, dome-like pressure sensors in the Rib design were produced and their sensor performance was evaluated. In the flat knitted form, Rib 3x3 with NP 15 possesses a high sensitivity of 0.71±0.01 kPa^{-1}. Apart from flat knitted structures, a dome-like pressure sensor in the Rib 3x3 form also possesses a potential design with a quick response time and a good sensitivity.

Flat knitted can be directly attached to the skin or large area textiles and be utilized for human-computer interface systems. Dome-like sensors were found to be promising for tactile applications such as the detection of finger movements by pinch or pressure sensing mats for shape or object recognition. Also, the user can perceive the sensors as protrusions by touching them, which provides convenience in the application.

For future studies, dome-like pressure sensors will be evaluated in detail by changing the filler content, type of filler and the shape of the dome. The production of multiple dome-like pressure sensors will be done at one-go and be tested for pressure sensing performance.

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