COMPARATIVE ANALYSIS OF KNITTED PRESSURE SENSORS

Natalija Baribina, Alexander Oks, Ilze Baltina, Peteris Eizentals
Riga Technical University, Latvia
natalija.baribina@edu.rtu.lv, aleksandrs.okss@rtu.lv, ilze.baltina@rtu.lv, peteris.eizentals@gmail.com

Abstract. Textile sensors have a wide range of applications in wearable monitoring systems due to their lightweight, elastic and flexible properties. The present paper is devoted to the comparative analysis of effects of pressure load on knitted pressure sensors of different shapes and their durability to washing. All the developed sensors are knitted using cotton yarns and copper coated acrylic yarns on a circular knitting machine. The sensor performance properties and durability have been tested experimentally. Each type of sensors was tested under quasi-static and dynamic loadings with various pressure forces. Relations between the applied pressure force and sensor sensitivity and responses were analysed. It was found that filled shape sensors are more sensitive to low pressures. Testing of the sensors under dynamic loads confirmed high repeatability of measurements and sensitivity even to small variations of the loading level. One of the most common problems of textile-based sensors that essentially restrict application of smart textiles is their care. Therefore, durability of the designed sensors to washing was been studied, as well. It was found that knit density affects sensor durability to washing. Sensors with a higher knit density showmore stable and uniform electrical resistance increase, whereas sensors with a lower knit density show unstable durability and higher variation in electrical resistance changes. Also, configuration of the sensors affects the electrical resistance changes due to washing.

Keywords: knitted pressure sensor, performance, durability.

Introduction

Knitting technology combined with electronics has wide application possibilities. Using knitting technology different sizes and shapes of conductive elements can be produced rapidly and cost-effectively. Traditionally, e-textiles are made from conductive fibres, filaments, yarns and fabrics. Sometimes conductive coatings are used on raw materials to obtain conductivity. Their application and durability can be influenced by material suitability for manufacturing of smart textiles and wearing, and different environmental conditions. Thus, textile sensors reliability and sensitivity are one of the vital problems for successful e-textile functionality.

Soukup and Hamacek used silver coated polyamide threads for embroidering were repeatedly tested by humidity sensors at different relative humidity levels and measured after 5-20 washing cycles. The results demonstrated very good resistance to washing and the sensors performed well during cyclic climatic test [1]. Textile based path ways have been tested after 10 washes in [2]. The electrical resistance values of all characteristic samples increased up to 2.5 times. It was concluded that the coarser the yarn, the greater the resistance increase in the silver-plated samples.

Influence of coatings on the durability of textiles is being studied increasingly. New methods to make long-life textiles are being searched constantly. In Rehnby's [3] studies commercially available inherently conductive polymers mixed with an acrylic binder polymer at different concentration and applied to a polyester fabric were used. The fabrics were subjected to aging for 408 h and to shear, flexing, heat, rubbing and abrasion resistance tests. It was found that samples with a more active conductive polymer on the surface showed a higher resistivity after exposure to heat and aging with humidity. In Kellomaki's research the protective coatings used for wearable antenna tags were compared after washing [4]. Six coating materials were tested, and it was found that after coating and drying only silicone and latex remained flexible, whereas others became hard. No changes in the same printed antennas could be seen after ten washes, apart from the colour change. The epoxy coating on copper fabric tags applied in another study [5] demonstrated potentially good protection against humidity and detergents for 15 washing cycles despite strong mechanical stresses. Dong and Wang [6], using silicone rubber coated three-ply twisted stainless steel/polyester fibre blended yarns, have shown how to create stretchable and washable self-charging power textile applying the weft knitting technology. Unfortunately, the technique was not adaptable to industrial knitting because the resulted yarn thickness was too high.

In the recent years conductive polymers have a more significant role in the development of smart textiles. So, reusability and durability of corresponding smart textiles are important topics of research. Takamatsu used a commercially available conductive polymer to cover an interlock knit to fabricate

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electrodes for electrocardiography. The electrodes were re-used after one month and were still able to record [7]. In another research dip-coated textiles were washed 50 times and after that also showed good durability [8].

Reliability of conductive knitted elements to the cyclic stretching was shown in [9]. In [10] comparative analysis of knitted wet and dry electrodes for physiological information monitoring has been presented. Within a short period, the wet electrode system performance was degraded with time, whereas a better performance was observed in dry electrodes for more than a 2-hour period of operation. Also, a new type of knitted electrodes to produce muscle contractions was presented in another study [11]. The laboratory tests have been performed with neurostimulators, which are usually used in rehabilitation clinics, to test their effectiveness during walking rehabilitation exercises. In [12] moisture detection speed of woven and sewn humidity sensors was compared, where a sewn sensor had a faster response, whilst a woven sensor was less sensitive to perspiration simulation. Knitted antennas [13] had been applied using a medical programmable mannequin for infant breathing monitoring. This research showed that sensors could be used for applications where mechanical movement caused stretching. Other study [14] has been carried out with four knitted conductive textiles during 500 cyclic loadings. It was discovered that after an initial preconditioning round of testing the stabilisation of the electrical behaviour was faster and more repeatable.

The present paper is devoted to studying of properties of developed knitted sensors. The sensors fulfil the function of pressure transducers. To define the properties of the sensors they were tested using quasi-static and dynamic loadings. Durability of the sensors was determined by the washing impact on electrical resistance changes of the sensors.

Materials and methods

Three types of sensors reviewed in the paper (Fig. 1) were obtained using the weft knitting technology with industrial knitting machines. Sensors were made from an acrylic copper coated spun yarn and a cotton yarn plated with polyamide or elastane.

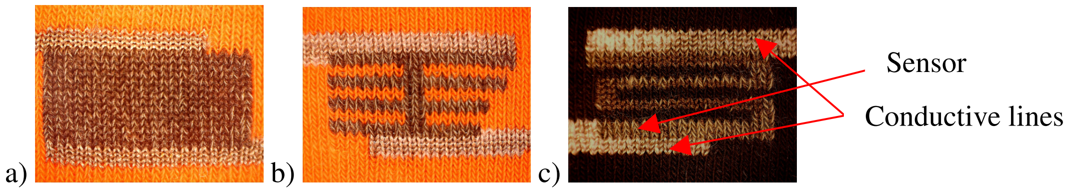

Fig. 1. **Knitted pressure sensors:** a –Type A; b –Type B; c –Type C

Type A sensor filled area consists of 21 wales and 14 courses. Type B ribbed shape sensors consist of horizontal ribs and a central axis. The central axis width is 2 wales and each line height is 2 courses. Type C sensor has a curved configuration changing from 3 courses to 3 wales by turns.

Quasi-static and dynamic tests were performed during the study. Quasi-static tests were performed for all sensors. The basic knit density of samples is 97 wales x 133 courses/10 cm. The dependence sof electrical resistance of the sensors from the applied pressure forces were recorded using complex of Zwick/Roell Z2.5 and Agilent 34970A with module 34901A. Dynamic tests were conducted on Type B and Type C sensors using INSTRON E1000 and a custom-made device for resistance monitoring [15]. Testing conditions during quasi-static and dynamic tests are summarized in Table 1.

Table 1

Sensor dynamic and quasi-static test conditions

Characteristic	Dynamic test	Quasi-static test
Loading range, kPa	150	255, 380, 640
Loading rate, kPa·s^{-1}	300, 450	25
Relaxation time	0.25 sec	-

Within the framework of the study a wash test was performed to determine the minimum number of care cycles sensors as well. A wash test was performed forType B and Type C sensors. In the preparatory tests with sensors it was observed that filled shape sensors (Type A) hada lower electrical resistance than it is necessary for a pressure sensor. It is important to obtain sensors with a high enough electrical resistance to detect separate signals from them and the conductive lines. That is why Type A sensors were not washed. It should be noted that Type C sensors had two different knit densities – the abovementioned 97 wales x 133 courses/10 cm (Type C) and also 85 wales x 108 courses/10 cm (Type C2).The electrical resistance of the sensors was measured after each washing cycle manually by using a digital multimeter. Contacts of the multimeter were connected with conductive lines (see Fig.1) as near as possible to the tested sensor. The electrical resistance of the unloaded sensors was measured 10 seconds after the prepressing weight was removed (sensor loaded by 20 kPa force for a few seconds before each measurement). Electrical resistance of the pressed sensorwas measured 10 seconds after the weight was imposed on it (100 kPa). To compare the electrical resistance changes due to washing only the data of loaded sensors were used.

Results and discussion

Quasi-static test. Electrical resistance measurements are recalculated to inverted dependences $1/R(p)$and normalized (Rmax/R). Normalized inverted dependences of three types of sensors are presented in Figure 2.

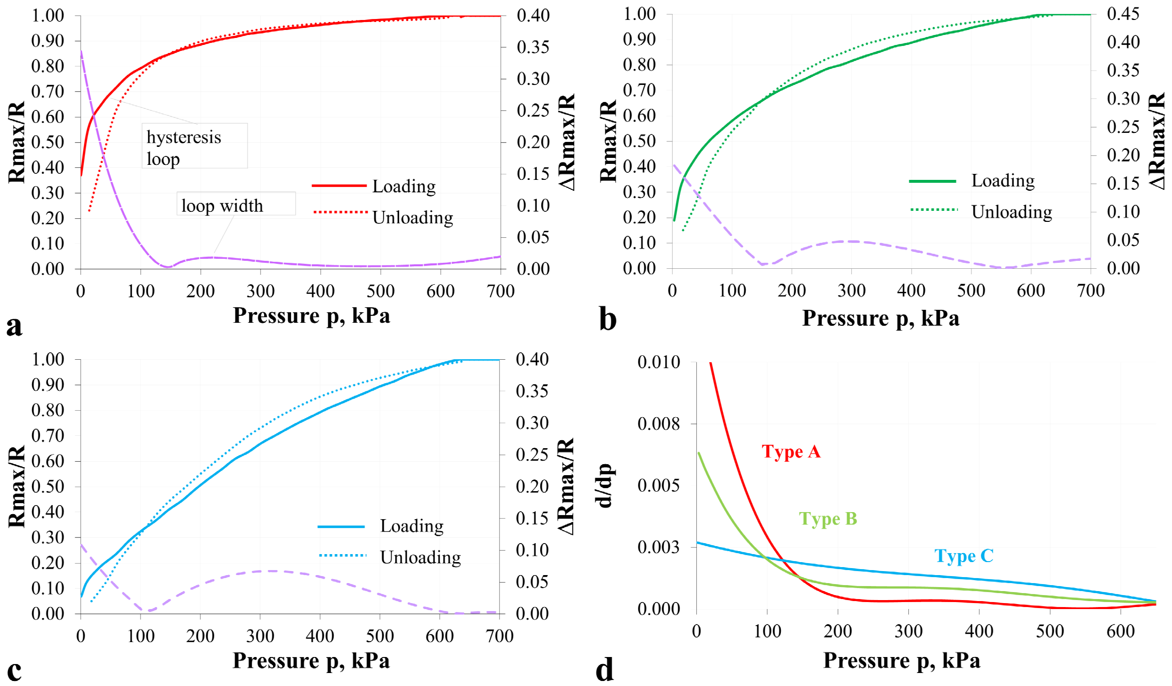

Fig. 2. **Quasi-static test results:** a – Type A; b – Type B; c – Type C; d – sensitivity of sensors

As it can be seen from Fig. 2a – c, the dependences Rmax/R have the form of hysteresis loops. The height of the hysteresis loop (ΔRmax/R function) is the difference between loop's loading and unloading branches and is depicted with a dashed line.The closer value of ΔRmax/R function to 0, the smaller is the difference between loading and unloading sensor Rmax/R readings. The sensitivity of the sensors is represented by the derivative $^{d}/_{dp}$ of the hysteresis loop-forming functions(Fig. 2d). Hence, the design of a sensor affects sensitivity to pressure fluctuations. Type A(Fig. 2a) sensor has the highest sensitivity at lower pressures. Electrical resistance of Type A sensors increases rapidly during loading until the pressure reaches 150 kPa and then increasing becomes slower and reaches saturation. This relevance is clearly visible in Fig. 2d, where exceeding 200 kPa the sensor becomes almost insensitive to pressure. Type C sensors demonstrate lower sensitivity at pressures up to 100 kPa, butin general the function of the applied pressure forces and normalized inversion dependencies is nearly linear (Fig. 2c). Sensors of this type also demonstrate higher sensitivity at high pressures (Fig. 2d). Type B sensor has a medium sensitivity between A and C.

Depending on the purpose of application, sensors could be selected by their sensitivity characteristics. Filled square sensors have a simple shape; they are easier to design compared to others, however, they work better at low pressures. On the other hand, curved line sensors are more sensitive to pressure regardless of the force applied.

Dynamic test. The loading rates applied in dynamic tests give the possibility to imitate walking. The loading rate of 255 kPa·s^{-1} corresponded to normal walking speedof 4.75 km·h^{-1}, while the loading rate of 380 kPa·s^{-1} corresponded to accelerated walking speed of 5.9 km·h^{-1}.In the graphs the curves of the pressure force and inverted values of electrical resistance applied to sensors are depicted on the time scale, starting from the 10th second of the test.

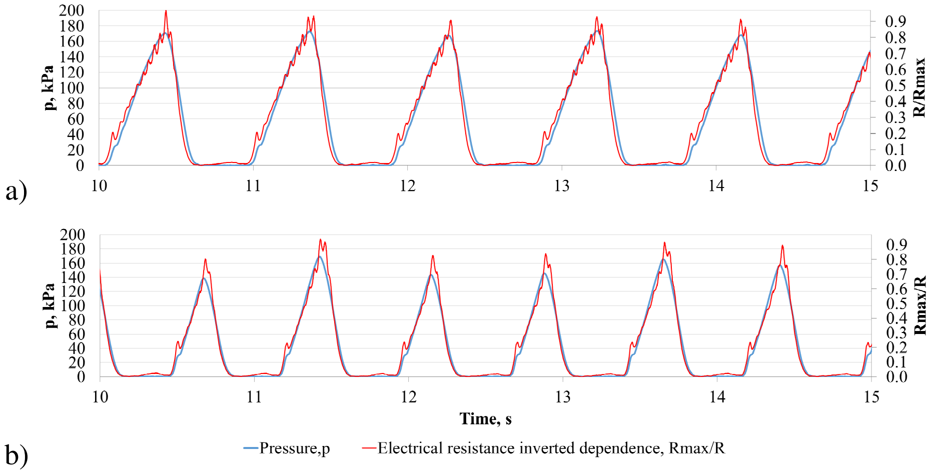

Fig. 3. **Type B sensors dynamic test results:** a – loading rate 255 kPa·s^{-1}; b – loading rate 380 kPa·s^{-1}

*R*max/*R* measurement peaks of Type B sensors coincide on the time scale. A slight mismatch (0.2 s) is observed during compression and relaxation periods. The electrical resistance measurement curves with pressure increasing are irregular zig-zag-shaped (Fig. 3a). It may be due to the use of an insufficiently rigid template, on which the sensors were placed and fixed. However, as the compression rate increases the curves become smoother and coincide in time (Fig. 3b).

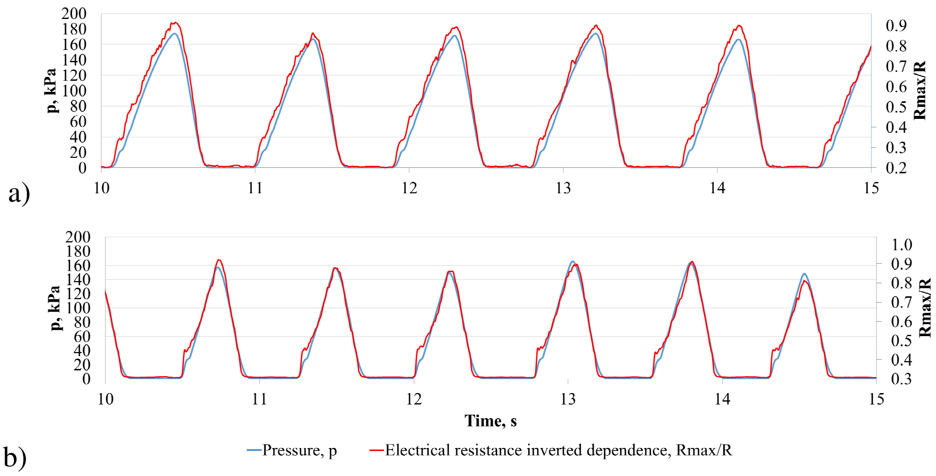

Fig. 4. Type C sensor dynamic test results: a – loading rate 255 kPa·s^{-1}; b – loading rate 380 kPa·s^{-1}

Also, the peak values of *R*max/*R* curves in Type C sensors coincide in time (Fig. 4a). Moreover, the higher the compression speed, the more similar the curves are (Fig. 4.b). In comparison with Type B sensors the increase curves for Type C sensors form a closer relationship between the applied load and the *R*max/*R* curves. The results of both sensors' dynamic tests show a good tendency – a coincidence of the pressure force and the inverse values of electrical resistance. At a lower test speed there can be seen a shift in graphs during the compression and relaxation periods, but the peak values are practically at the same level. In contrast, at a higher compression rate the curves are even smoother, whereas the amplitude peak values vary.

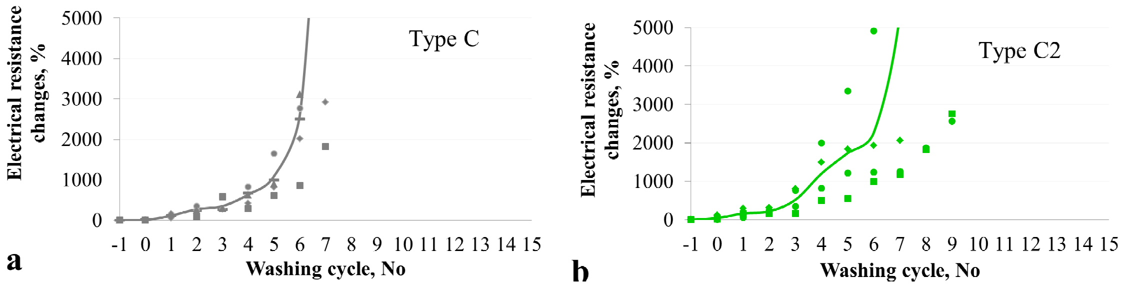

Fig. 5.**Electrical resistance changes ofType C sensors after washing:** a –Type C; b – Type C2

Washing test. Figure 5 shows electrical resistance changes in Type C sensors with two different knitting densities. Sensors with a higher knit density in Figure 5a have a more stable electrical resistance and it increases more uniformly. Sensors with a lower knit density show unstable durability and a higher variation in electrical resistance changes, shown in Fig. 5b.

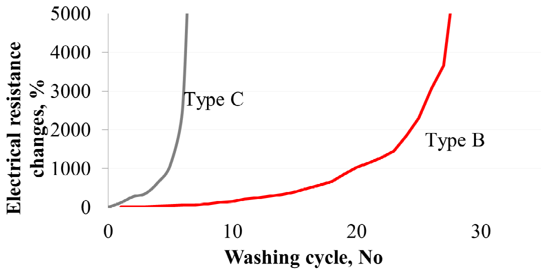

Fig. 6.**Comparison of Type B and Type C sensors after washing**

Figure 6describes electrical resistance changes in Type B and Type C sensors after washing. Type C sensors can be washed 6/7 times on average, whereas Type B sensors – more than 27 times until electrical resistance increases more than 20 times. The electrical resistance of Type B sensors increases more evenly, whereas the electrical resistance of Type C sensors increases rapidly. The result can be related to the sensor current flow path. Type C sensor conductive line is longer; consequently it is more subjected to mechanical, water and detergent impact during washing. The results of the experiment show that Type B sensors are more suitable for intensive washing.

Conclusions

Depending on the intended application it is necessary to select suitable sensor characteristics from sensitivity and reliability relation. Upon completion of the study the following conclusions have been made:

1. The simplest shape Type A sensors show the highest sensitivity at low pressures compared to other types.
2. Type C sensors show a uniform sensitivity and present a practically linear function between the pressure force and electrical resistance increase.
3. Type B and Type C sensors are suitable for dynamic loads and their response rate and pressure force curves coincide on a time scale.
4. Type B sensors demonstrate better washability and therefore they are more suitable for frequent washing.

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