# Suitability of knitted fabrics as elongation sensors subject to structure, stitch dimension and elongation direction

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## Abstract

The area of smart textiles has recently attracted more and more attention. One of the challenges in this domain is the development of textile sensors, such as textile electrodes, pressure sensors, elongation sensors etc., mostly containing conductive yarn and/or conductive coating. One possibility to build a textile elongation sensor which can, e.g., be utilized as a breathing sensor in a smart shirt, is using knitted fabrics created from conductive yarns, which often show a strong dependence of the electric resistance on the elongation. Due to the typical wearing out of knitted fabrics, however, the time-dependent behaviour of a stretched fabric must also be taken into account. The article thus shows the results of elongation-dependent and time-dependent resistance measurements on knitted fabrics, produced from different yarns in various structures and stitch dimensions, elongated in different orientations with respect to the course direction. The results of our study show that full cardigan with medium stitch size is better suited for use as an elongation sensor than double face fabrics or other stitch sizes. These findings are not influenced by the stainless steel fraction in the conduction yarn, while mixing this yarn with a non-conductive one causes undesired signal deviations.

**Keywords:** Elongation sensor, conductive fabric, knitted fabric, stainless steel fibre yarn, cotton yarn, elongation direction

The idea of using conductive yarns in knitted fabrics has been described recently in several theoretical and experimental papers. Possible applications of conductive knitted fabrics contain electromagnetic shielding,[1,2] textile pressure sensors,[3] anti-electrostatic textiles[4] or knitted electronic circuits,[5] but most often, they are used as elongation sensors.[6,7]

Theoretical investigations of the electromechanical properties of knitted fabrics can be based on a hexagon resistance model simulating the loop structure of single face fabrics, allowing for the resistance to be calculated in dependence on the extension by circuit network equations.[8-11] A similar approach for conductive 1x1 rib fabrics[12] leads to a calculation of the extension-dependent resistance for this structure. Other models taking into account the superposition of length-related resistance and contact resistance can be used to calculate the resistance for unidirectionally extended knitted fabrics.[13,14] Some experimental findings showed that the elongation dependence of the resistance is mostly based on the change of contact resistance between the yarns during stretching,[10,15] while this result is inversed in the large-strain regime.[9]

The large number of experimental investigations on this subject, however, shows that the theoretical models can only help to develop a basic understanding of the situation in a stretched conductive knitted fabric, while several effects are not yet included in these simulations. A study using silver-plated nylon and elastomeric yarns, e.g., pointed out the significant influence of manufacturing parameters such as knitted structure, gauge, yarn input tension, and the characteristics of the elastomeric yarn.[16] Strong relationships between fabric parameters and electromechanical properties have also been reported for interlock structures created with silver-coated yarn,[17] leading to qualitatively different hysteresis loop shapes for different elastic yarn input tensions, elastic yarn linear densities, and wale and course densities.

One of the largest problems impeding the use of conductive knitted fabrics as elongation sensors is the occurrence of large elastic hystereses during deformation. One possibility to enhance the electromechanical properties of knitted elongations sensors is the use of hybrid yarns containing a conductive and an elastomeric part.[18] Other experiments have shown that exchanging the usual stainless steel fibre yarns by carbon fibre yarns can enhance the repeatability of the strain-dependent resistance values, which can be explained by reduced friction between the carbon fibres[15,19] – an idea which cannot always be implemented in textile sensors used in garments due to the well-known brittleness of carbon fibres.

In this article, we thus examine the reliability of elongation measurements with conductive yarns containing stainless steel fibres by investigating the elongation dependence as well as the time dependence of the resistance of fabrics knitted with different structures. Instead of producing hybrid yarns, the effect of which has already been examined in Ref. 18, we concentrate on different conductive yarns and hybrid fabrics composed of conductive and non-conductive yarns. Additionally, we examine the possibility to use elongation directions other than the course direction.

## Experimental

The fabrics used in this study have been produced on a Stoll CMS-302 TC flat knitting machine with gauge E8 (stitch cam setting NP = 9.5 (small stitches), 10.5 (middle sized stitches), or 11.5 (large stitches), carriage speed 70 cm/s, one system). Amongst other structures (not shown here), double face and double cardigan fabrics have been knitted (see Fig. 1 for notation).

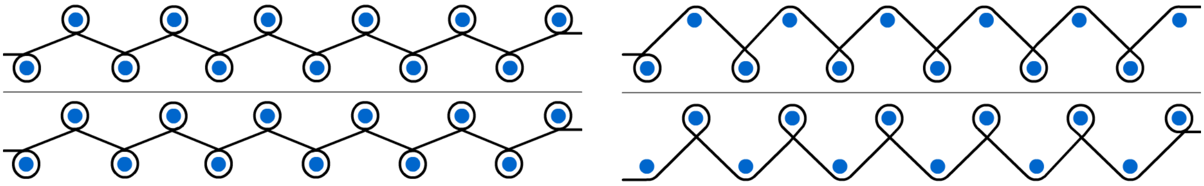

Fig. 1: Knitting notations of double face (left panel) and full cardigan (right panel).

The fabrics mainly consist of the staple fibre yarn “S-Shield” (Nm 50/2) made by Schoeller, Bregenz (Austria), which contains 20 % thin stainless steel fibres and 80 % polyester (PES) fibres (average resistance $R = (525 \pm 57)$ kΩ/m). The twist is for single yarn - 600 Z t/m, for the folded yarn - 425 S t/m, the tenacity is (673 ± 37) cN, and the elongation - (15.1 ± 0.8) % (yarn specifications according to Schoeller data sheet). The S-Shield has been used as single thread, as two threads, or in combination with a cotton thread. Additionally, another S-Shield yarn with the yarn count Nm 15/1 containing 50 % stainless steel fibres and 50 % polyester (average resistance $R = (245 \pm 43)$ kΩ/m) has been used to examine the influence of different fractions of conductive material in the yarn.

Table 1 gives an overview of the samples under examination for which the results are depicted in this article.

Table 1: Definition of the samples described in this article.

| **Yarn** | **Structure / stitch dimension** | **Wales / cm** | **Courses / cm** | **Loop length / mm** |
|---|---|---|---|---|
| S-Shield 50/2, 2 threads | Double face / medium stitches | 3.9 | 7.3 | 7.9 |
| S-Shield 50/2, 2 threads | Full cardigan / small stitches | 2.8 | 8.6 | 7.5 |
| S-Shield 50/2, 2 threads | Full cardigan / medium stitches | 2.4 | 7.1 | 6.4 |
| S-Shield 50/2, 2 threads | Full cardigan / large stitches | 2.2 | 6.0 | 6.2 |
| S-Shield 50/2, 1 thread | Full cardigan / small stitches | 2.8 | 7.7 | 7.3 |

| | | | | |
|---|---|---|---|---|
| S-Shield 50/2 + Cotton | Full cardigan / small stitches | 3.0 | 8.2 | 5.4 |
| S-Shield 50/2 + Cotton | Full cardigan / medium stitches | 2.5 | 6.2 | 7.0 |
| S-Shield 15/1, 1 thread | Full cardigan / large stitches | 1.8 | 5.3 | 8.4 |

For all experiments, samples of 40 cm x 6 cm (width x height) were cut from the fabrics to ensure equal experimental conditions. Conductive clamps, to which a multimeter was fixed, were used to hold the left and the right side of the fabric. The original – unstretched – length of the fabric between the clamps was 35 cm. If not described differently, the elongation direction is identical to the course direction.

For the elongation-dependent measurements, the fabrics were stretched from lower to higher elongations, with each resistance value taken after a period of 5 s at the respective elongation.

For the time-resolved measurements, the fabrics were pre-elongated for 30 minutes from 35 cm between the clamps to a length of 40 cm (relative elongation of 0.14); the measurements were then taken after another elongation to 45 cm (relative elongation of 0.29). This procedure has been used to simulate typical applications, such as a breathing sensor,[20] where the material is always subject to a certain elongation, the deviations of which are measured.

Fig. 2 depicts the length scales as well as the measurement procedures for elongation dependent (upper panel) and time-dependent measurements (lower panel).

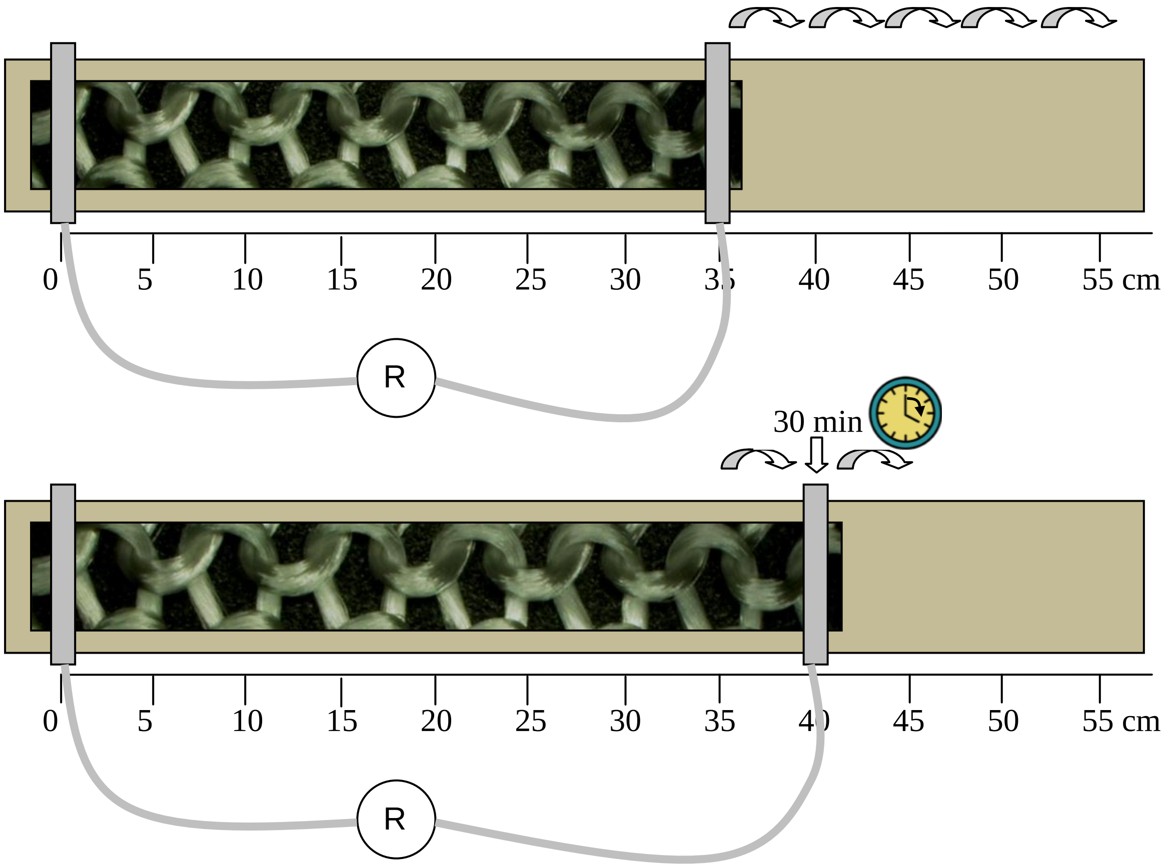

Fig. 2: Sketches of elongation-dependent (upper panel) and time-dependent measurements (lower panel) of the resistance *R*.

## Results

In a first series of experiments, different knitted structures have been examined, amongst others double face, single face, Milano rib, and full cardigan. Fig. 1 shows a comparison of double face and full cardigan, two structures which exhibited the most stable time-dependence and elongation-dependence in first tests, while single face fabrics, e.g., often depicted an oscillatory time-dependence and Milano rib led to a very small elongation dependence of the electric resistance. On the y-axis, the relative resistance $R / R_0$ (resistance / resistance for zero elongation) is depicted, with $R_0$ equal to the resistance measured in the initial relaxed state.

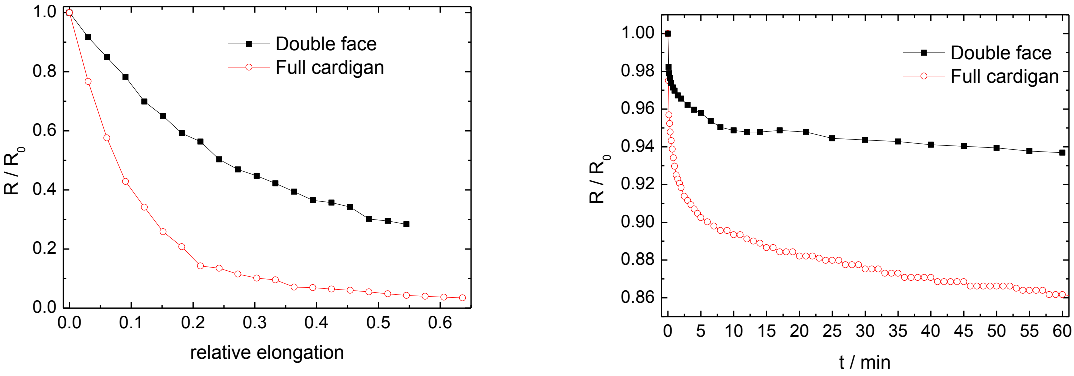

Fig. 3. Comparison of elongation-dependence (left panel) and time-dependence (right panel) of the relative resistance change in conductive double face and full cardigan knitted fabrics.

The relative resistance, scaled on the value of $R_0$, is decreasing for the complete range of elongation which is measured here. Depending on the conductive yarn and the knitted fabric construction, especially on the question whether there are non-conductive courses introduced between the conductive courses, some experiments show an increase of the resistance during elongation,[16,17] while the resistance normally decreases in examinations of fabrics knitted completely from conductive stainless steel yarn,[20,21] sometimes connected with an initial increase of the resistance (cf. Fig. 5, left panel) for a mixture of conductive and non-conductive yarns.

The relative resistance change, dependent on the elongation (Fig. 3, left panel), is significantly stronger in full cardigan than in double face fabrics, especially for small relative elongations. This can be explained by the fabric structures – while in a double face fabric, elongation firstly leads to unfolding the typical rib structure,[21] in full cardigan structures an elongation directly starts changing the forces between the connected yarns in the contact areas, leading to a larger resistance change.

On the other hand, full cardigan fabrics also have a stronger time-dependence than double face fabrics (Fig. 3, right panel). For an elongation sensor, a structure with small time dependence and large elongation dependence would be ideal. Comparing the absolute values of the elongation-dependent resistance changes $R/R_0$ – i.e. the desired effects – with the absolute values of the time-dependent resistance changes – which can be treated as an estimate of the expected error for long-time measurements –, full cardigan is apparently preferable, especially for smaller relative elongation values.

Thus, for the next experiments, only the results of full cardigan fabrics are depicted; double face fabrics, however, showed qualitatively similar effects.

In the next experiment, the influence of the stitch dimensions is examined. Fig. 4 shows the elongation-dependence (left panel) and the time-dependence (right panel) of the resistance of full cardigan fabrics knitted with two S-Shield Nm 50/2 threads and different stitch dimensions. While the time-dependence (right panel) becomes larger for larger stitch sizes, the elongation-dependence of medium and large sized stitches does not differ significantly. Thus small or medium sized stitches are better suited for utilization in an elongation sensor than large sized stitches. Comparing the absolute values of $R/R_0$ for both graphs again, it can be concluded that medium-sized stitches are advantageous compared to small sized stitches for use of the knitted fabrics as elongation sensors.

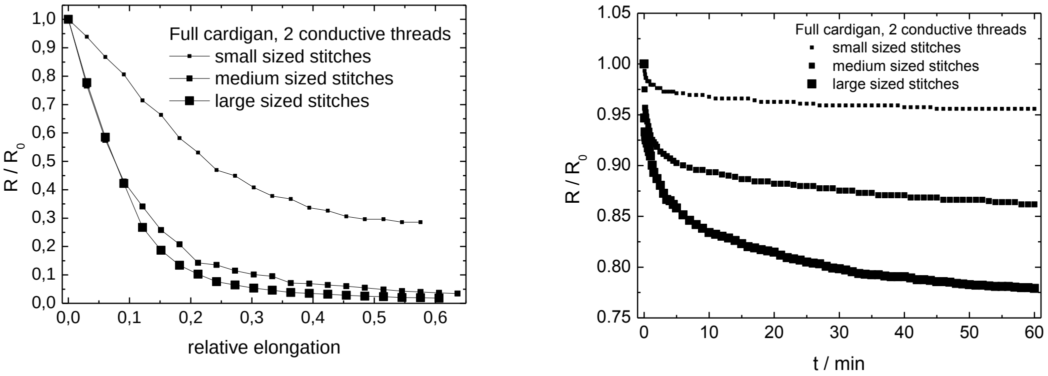

Fig. 4. Comparison of elongation-dependence (left panel) and time-dependence (right panel) of the relative resistance change in conductive full cardigan knitted fabrics with different stitch dimensions.

Next, different materials and material combinations are compared. Fig. 5 shows the elongation-dependent (left panel) and time-dependent resistance (right panel) of different full cardigan fabrics, knitted from one conductive thread (S-Shield 50/2 with 20 % stainless steel fibres or S-Shield 15/1 with 50 % stainless steel fibres) and sometimes one additional non-conductive thread. While the single-thread knitted fabric from pure S-Shield 50/2 and the fabric knitted from S-Shield 15/1 behave quite similarly to the results shown in Fig. 4 (both panels), the fabrics knitted from S-Shield and an additional cotton thread show strong deviations from the smooth curves of the single-material fabrics in the time-dependence (right panel) as well as an unusual relation between $R$ / $R_0$ and the relative elongation. Especially, for small elongations, one value of $R$ / $R_0$ can be found for two different elongations. Such mixed-material fabrics can be expected to cause undesired ambiguous results if used as sensors. Thus it is apparently not recommended to mix conductive and non-conductive yarns in a knitted elongation sensor, while the results are independent from the amount of stainless steel in the conductive yarn. This finding should be taken into account especially if the combination with an elastane yarn is planned to enhance the form stability of the knitted fabric.

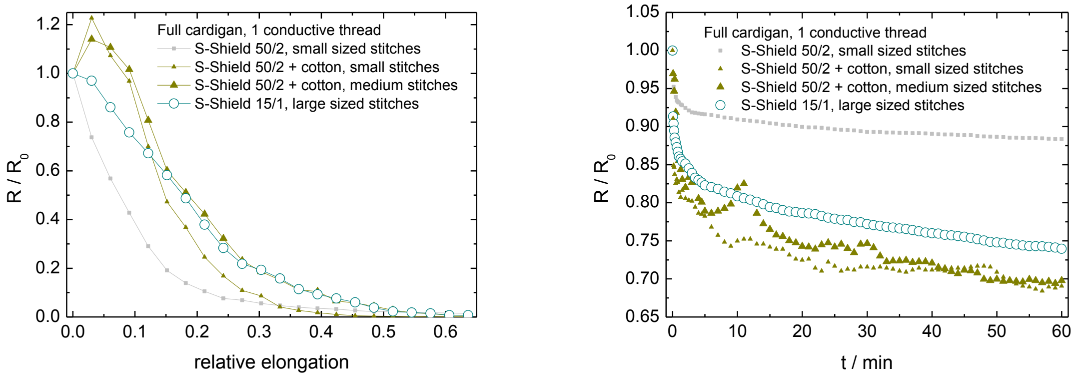

Fig. 5. Elongation-dependence (left panel) and time-dependence (right panel) of the relative resistance change in full cardigan fabrics knitted from different yarns.

As a last test, different elongation directions were examined for full cardigan fabrics knitted with two threads (Fig. 6). Interestingly, in both graphs the 0° direction differs strongly from the other sample orientations. In the elongation dependence, fabric orientations of 30° to 90° between courses and elongation direction are clearly preferable to the usual 0° orientation. Also taking into account the time-dependence, where the smallest values are ideal, ~ 30° is a good compromise between strong elongation-dependence and not too strong time-dependence of the resistance change. Additionally, the knitted fabrics can be drawn to a larger extent for smaller angles, which also supports the idea of using a fabric cut at an angle of 30° with respect to the courses as elongation sensor.

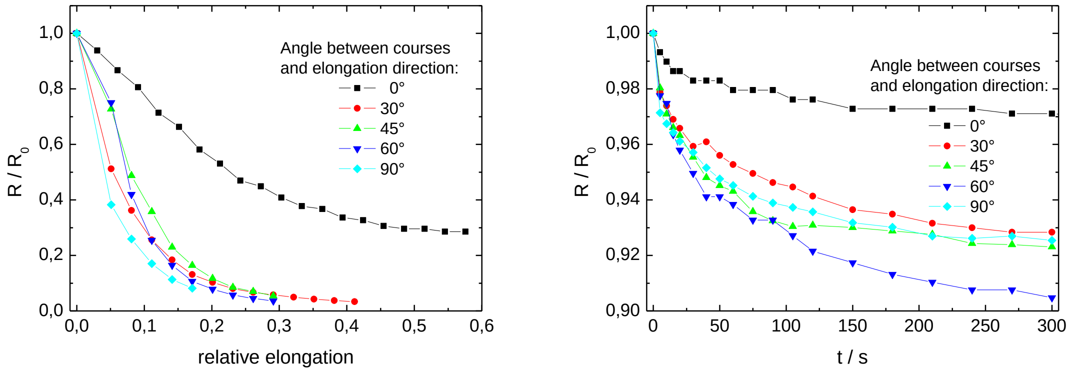

Fig. 6. Comparison of elongation-dependence (left panel) and time-dependence (right panel) of the relative resistance change in conductive full cardigan knitted fabrics measured in different elongation directions.

## Discussion

A detailed comparison of the results shown in the figures above is given in Fig. 7, the values for double face fabrics with the three different stitch dimensions are added. The bars depict the relative resistance change $\Delta R/R_0$ for a relative elongation of 0.1 (maximum value to be expected for a breathing sensor); the error bars show the difference of $R/R_0$ measured after 5 minutes in the time-dependent measurements.

Principally, a knitted fabric is ideally suited as an elongation sensor if the relative resistance change is high and the time-dependence (the error bar) small. The most problematic fabrics are those composed of S-Shield and cotton, with the “errors” larger than the signals. The highest signals are measured for full cardigan, on the one hand for small stitches knitted with only one thread – which leads to quite an open and instable fabric – and on the other hand for full cardigan fabrics which are not elongated along the courses (i.e. along 0°), but under a certain angle with respect to the courses – where the problem of too instable fabrics can be overcome.

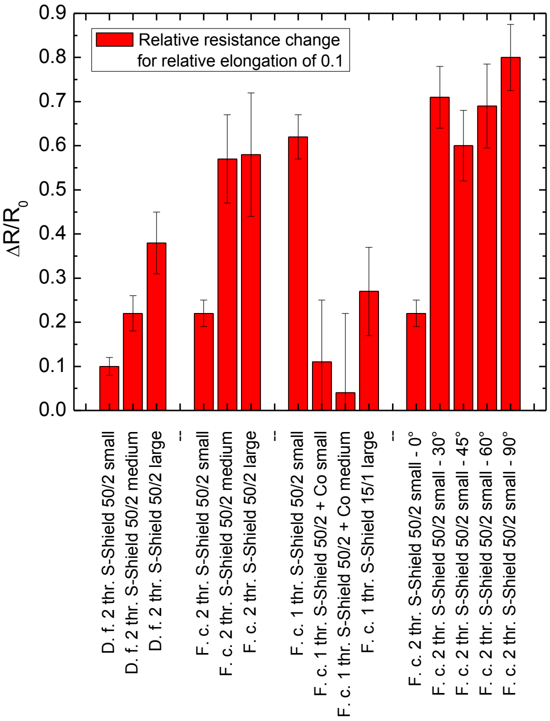

Fig. 7: Comparison of different structures knitted from various yarns, as described before. D. f. = double face, F. c. = full cardigan, thr. = threads. The relative resistance change $\Delta R/R_0$ is defined as 1 - $R/R_0$ and has been detected here for a relative elongation of 0.1. The error bars

show the difference of $R/R_0$, detected in the time-dependent measurements after a time of 5 minutes.

Comparing the different parameters under examination in this article, the best choice for a knitted elongation sensor, produced from stainless steel yarn with a basic knitting structure, is thus a full cardigan with small or medium stitch size, cut to strips oriented ~ 30° from the course direction. No large differences occur between different numbers of threads and different fractions of stainless steel in the yarn, while mixing with non-conductive yarns can lead to significant undesired signal fluctuations superposing the measurement signal. Further examinations should therefore concentrate on possibilities to include elastane to provide a better form stability, e.g. by plating, and on tests of less basic knitting structures, which may lead to even better results.

## Conclusion

Double face and full cardigan fabrics, knitted from different conductive and partly also non-conductive yarns, have been examined with respect to their elongation-dependent and time-dependent conductivity changes. While elongations of 20-60 % can cause a decrease of the electric resistance of 90 % or even more, depending on the yarn and fabric parameters, time-dependent resistance decreases of up to 30 % are also possible and must be taken into account during the selection of ideally suited fabrics and yarns for knitted elongation sensors. Especially for breathing sensors, it should be mentioned that heavy breathing changes the breast circumference by only ~ 10 %, a value which still leads to a decrease of the electric resistance of 60-80 % for several fabrics. Amongst the samples under examination, full cardigan with medium stitch size, with the elongation direction tilted with respect to the courses, gave the best results, while mixing conductive and non-conductive yarns has shown to cause undesired signal deviations.

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