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Article

Advancing Smart Textiles: Structural Evolution of Knitted Piezoresistive Strain Sensors for Enabling Precise Motion Capture

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Abstract: Recently, there has been remarkable progress in the development of smart textiles, especially knitted strain sensors, to achieve reliable sensor signals. Stable and reliable electro-mechanical properties of sensors are essential for using textile-based sensors in medical applications. However, challenges associated with significant hysteresis and low gauge factor (GF) values remain for using strain sensors for motion capture. To evaluate these issues, a comprehensive investigation of the cyclic electro-mechanical properties of weft-knitted strain sensors was conducted in the present study to develop a drift-free elastic strain sensor with a robust sensor signal for motion capture for medical devices. Several variables were considered in the study, including the variation of the basic knit pattern, the incorporation of the electrically conductive yarn, and the size of the strain sensor. The effectiveness and feasibility of the developed knitted strain sensors are demonstrated through experimental evaluation, by determining the gauge factor, its nonlinearity, hysteresis and drift. The developed knitted piezoresistive strain sensors have a GF of 2.4, a calculated drift of 50 %, 12,5 % hysteresis, and 0.3 % nonlinearity in parts.

Keywords: wearables; smart textiles; textile strain sensor; motion monitoring; medical applications

1. Introduction

Smart textiles offer tremendous potential in healthcare, providing solutions for monitoring vital parameters, facilitating rehabilitation, and improving overall well-being. Various studies have explored the integration of smart textiles into clothing and wearable devices for continuous health monitoring. These devices have demonstrated the ability to collect physiological data, track movement, and provide personalized feedback to patients and healthcare professionals [1–5].

A key aspect of this research work are medical smart textiles, for example, motion analysis for rehabilitation applications, or it serves as a signal for electrodes that are intended to stimulate specific muscle groups, e.g., to help people with peroneal nerve paralysis to walk or to train the muscle groups specifically through stimulation [6]. Pressure sensors are one way of analyzing movement, as shown in studies [7–9]. However, all existing solutions for motion detection have been realized via pressure sensors, which were applied to a garment afterwards and not integrally, processed in a manufacturing step and cannot be considered for the knitted piezoresistive strain sensor.

Another option to record the movement is through strain sensors [10,11], which work according to the piezoresistive effect [12,13]. Using piezoresistive strain sensors, placed on joints, the change in the electrical resistance of the piezoresistive strain sensor during mechanical deformation [14,15] can be used to infer the joint bending and, thus, the wearer's movement [2,16,17]. However, in addition to the position of the sensors, the conductive material, the structural implementation and the design are also important for the sensor functionality. Typical fibre-based conductive materials and their influence on the stability of the sensor signal are analysed in [15,18,19]. It was found that metalized

yarns are suitable in principle, but that the elongation of the base material plays a significant role in the sensor signal of a piezoresistive strain sensor and that less stretchable steel yarns are not suitable in contrast to silver-plated polyamide yarns. In [19–22] for example the performances of different knitted piezoresistive strain sensors were investigated. The authors explore the optimization of design parameters to achieve enhanced sensitivity and accuracy in strain measurements. The findings demonstrate that the selection of the conductive area and the design of the sensor profile have a significant influence on the performance of knitted piezoresistive strain sensors and are crucial aspects in the development of such sensors. The basic textile structure of the sensors was incorporated exclusively into a mock rib knit (similar to right-right-pattern). [23] focuses on addressing the challenge of hysteresis, which can negatively impact the accuracy and reliability of strain measurements. Through the utilization of specialized knitting techniques and careful selection of materials, the authors successfully design piezoresistive strain sensors that exhibit minimal hysteresis and provide a linear response to applied strain. The findings demonstrate the potential of weft-knitted piezoresistive strain sensors as reliable and accurate components in smart textiles, opening up opportunities for their integration into various wearables and healthcare applications.

In addition to the essential strain sensor development, various research approaches exist for motion capturing. Weft-knitted piezoresistive strain sensors are already used in various smart textiles for different applications, some of them can be transferred to medical applications. In Ref. [24], a smart glove was developed to measure the joint angles of the interphalangeal joints. It was shown here that knitted sensors would be suitable for motion capture. The finger movement with a knitted piezoresistive strain sensor was also developed an integrated in a wearable system in [25]. The new piezoresistive strain sensor has the potential to be used for medical smart textiles and the findings helps to do further research.

In addition to knitted piezoresistive strain sensors, other material approaches to motion sensing have been investigated. In [26], conductive elastomer sensors made of graphite and silicon rubber and in [27] carbon filled elastic rubber are coated onto a textile. Study [28] galvanized an elastic strain sensor made of silver-zinc oxide onto a knitted fabric, creating an electrically conductive sensor surface. These variants are also suitable in principle for joint angle measurement. These alternative material approaches are compared in the paper [14], and the advantages and disadvantages are discussed. It became clear that the coating variants still have significant weaknesses and must first be eliminated for medical applications.

Due to the enormous advantages of knitted piezoresistive strain sensors, this approach is focused on in this paper.

The studies discussed materials, designs, and the electro-mechanical behavior of knitted piezoresistive strain sensors. The development of knitted strain sensors with low hysteresis is challenging. The main findings from the literature research are:

- Steel-based conductive yarns are less suitable for strain sensors due to their low stretchability. Therefore, it is recommended to use silver-coated nylon yarns instead [15,18,19,22].
- The knitted pattern, in which the sensor yarns are integrated, should possess no plasticity and viscosity. Otherwise, the sensor's response will not be elastic, leading to hysteresis and drift effects [18,19].
- In the studies, mainly a right-right pattern has been used for the basic knit. The influence of other knitted pattern on the sensor performance was [18,20,21] not investigated. Moreover, it is therefore addressed in this study since it can be assumed that the pattern influences the sensor quality.
- The knitted pattern in [23] consists of only one elastic yarn, and the influence of inserting the strain sensor in stitch wale or stitch course direction was not analyzed. For this reason, the production direction of the sensors is considered as a criterion for selecting the correct sensor design.
- Only a few of the studies presented here have investigated the electro-mechanical properties of strain sensors under multi-cyclic mechanical deformation and thereby verified their suitability as strain sensors for motion capture a. o. in medical applications.

Therefore, in this research the principle of knitted piezoresistive strain sensors for motion capture for medical applications is explored. As shown by the presented studies, knitted textiles have

unique properties such as flexibility and stretchability, making them ideal for wearable applications. Knitted textiles additionally have the potential to create a weft-knitted piezoresistive strain sensor with low drift, hysteresis and nonlinearity, high elongation and gauge factor (GF).

2. Materials and Methods

Yarn Materials. In Table 1 the yarn materials and their characteristics are presented. Cellulose-based fibres Tencel-Lyocell (TL) and an elastic filament yarn (EY) form the basic pattern. The material is particularly suitable for use in medical devices worn close to the body as TL is kind to the skin, excellent in terms of moisture buffering and sensorial comfort [29]. The elastic yarn was also used to make the knit-ted fabric even more flexible and close-fitting for optimum skin contact for direct motion capture for therapeutic purposes. The SY was used to manufacture the textile-based piezoresistive strain sensors.

Table 1. Yarn materials used for the wearable piezoresistive strain sensor.

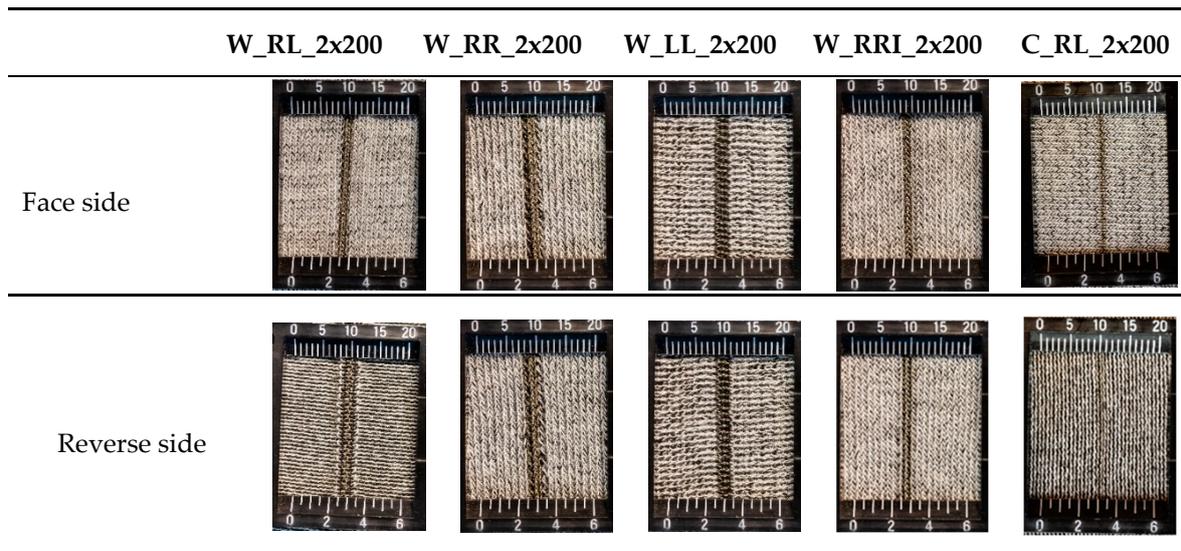
Producer	Name	Composition	Linear Density (dtex)	Resistance ($\Omega \cdot m^{-1}$)	Nomenclature
Gebr. Otto GmbH + Co. KG	Tencel-Lyocell-Std. Ringgarn	Tencel-Lyocell	25	-	TL
Jörg Lederer GmbH Elastic-Garne	Dorlastan 160 DC	Dorlastan/PA 6.6	270	-	EY
Amann & Söhne GmbH & Co. KG	Silver-tech+150	PA 6.6	220	< 300	SY

Manufacturing method. A flatbed knitting machine ADF 530-32 BW knit & wear from H. Stoll AG & Co. KG (Reutlingen, Germany) with the machine unit E7.2 was used to manufacture the piezoresistive strain sensors for enabling motion capture for medical and therapeutic applications. The knitted structures produced using the flatbed knitting machine had different textile parameters. These parameters are listed in the following Table 2.

Table 2. Textile parameters of the different patterns.

Production Direction	Pattern	Strain Sensor Width (mm)	Strain Sensor length (mm)	Nomenclature
stitch wale direction	right-left	1	200	W_RL_1x200
stitch wale direction	right-left	2	200	W_RL_2x200
stitch wale direction	right-left	4	200	W_RL_4x200
stitch wale direction	right-right	2	200	W_RR_2x200
stitch wale direction	right-right	4	200	W_RR_4x200
stitch wale direction	right-right-interlock	2	200	W_RRI_2x200
stitch wale direction	right-right-interlock	4	200	W_RRI_4x200
stitch wale direction	left-left	2	200	W_LL_2x200
stitch wale direction	left-left	4	200	W_LL_4x200
stitch course direction	right-left	200	2	C_RL_2x200

The nomenclature based on it is composed of Production direction_Pattern_Strain sensor widthxStrain sensor length, such as W_RL_1x200. Table 3 shows examples of the variants of the different knitted pattern used for the study.

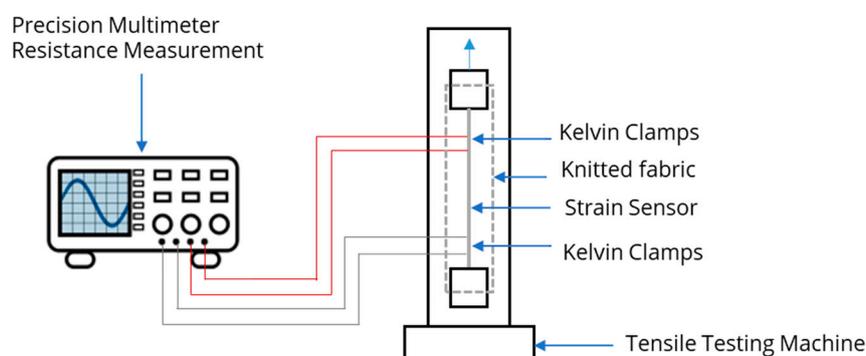
Table 3. Overview of the variance of the different patterns.

Measurement method. To determine the resistance change during cyclic mechanical elongation of the piezoresistive strain sensor, a four-wire-resistance measurement according to DIN EN 16812 [30] was used. The four-wire-resistance measuring station consists of a precision multimeter Keithley DAQ 6510 (Tektronix Inc., Beaverton, USA) to determine the measured values and a computer for data storage and processing. To stretch the specimen, the textile was clamped in the tensile testing machine Z2.5 (ZwickRoell GmbH & Co. KG, Ulm, Germany). The test regime is listed in the Table 4

Table 4. Parameters of the test regime.

Parameter	
Clamping length	200 mm
Preload	0,5 N
Testing speed	1000 mm/min
Strain in the range from	0 % to 50 % and 50 % to 0% in 10 % Steps
No. of cycles	10

To measure the piezoresistive strain sensor, it was fixed via four crocodile clips with a distance of 150 mm to each other (Figure 1).

**Figure 1.** Schematic measurement setup with precision multimeter, tensile testing machine and fixed piezoresistive strain sensor in four Kelvin clamps.

Analysis of electro-mechanical properties. In order to evaluate the sensor quality of differently knitted piezoresistive strain sensors, the electro-mechanical properties were determined. The gauge

factor (GF), its nonlinearity, hysteresis, and drift were calculated to analyze the cyclic sensor behavior. The software tool Matlab was used for the analysis. The nonlinearity was determined as the difference between the linear fit line Y and the real averaged result of R_{load} (Figure 2a) and was calculated with Equation **Error! Reference source not found.**

$$Y = ax + n \quad (1)$$

$$n \neq 0$$

The GF were derived from the slope of the linear fit. Equation **Error! Reference source not found.** presents the formulation for determining the gauge factor, where ΔR denotes the variation in resistance $\Delta R = R_{load} - R_0$, R_0 represents the initial resistance, and $\Delta \varepsilon$ signifies the strain alteration within the linear domain of the curve.

$$GF = \frac{\left(\frac{\Delta R}{R_0}\right)}{\Delta \varepsilon} \quad (2)$$

The hysteresis values were determined along the strain axis (horizontal), called strain hysteresis. The hysteresis strain, was defined as the maximum difference between the loading and unloading strains (see equation **Error! Reference source not found.**) [31].

$$H_\varepsilon = \max |R_{load} - R_{unload}| \quad (3)$$

In addition to the hysteresis as a measure of the sensor quality, the drift was determined last. The sensor drift is calculated by determining resistance at 0 % strain for every sample, averaging these values and determining the maximum deviation from R_0 .

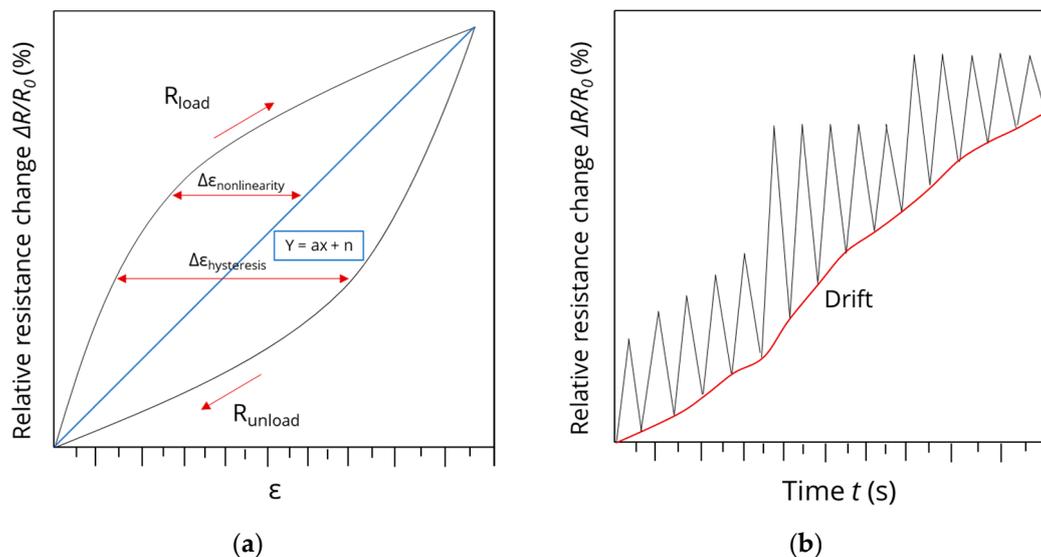


Figure 2. (a) is showing how to determine the nonlinearity and how to calculate the hysteresis; (b) is showing the baseline drift over time.

3. Results

3.1. Analyze various piezoresistive strain sensors in stitch wale - and stitch course direction

To comprehensively analyze various piezoresistive strain sensors, the initial phase involved assessing the electrical resistance in relation to strain and time. This assessment allowed for qualitative distinctions to be made. To illustrate the range of outcomes, we will focus on the $n_{nn_2 \times 200}$ variants as representative examples since these patterns offer the best overview of the differences between sensor designs. The first example is the knit production direction and the differences between stitch wale - and stitch course direction. The results are shown in Figure 3a,b.

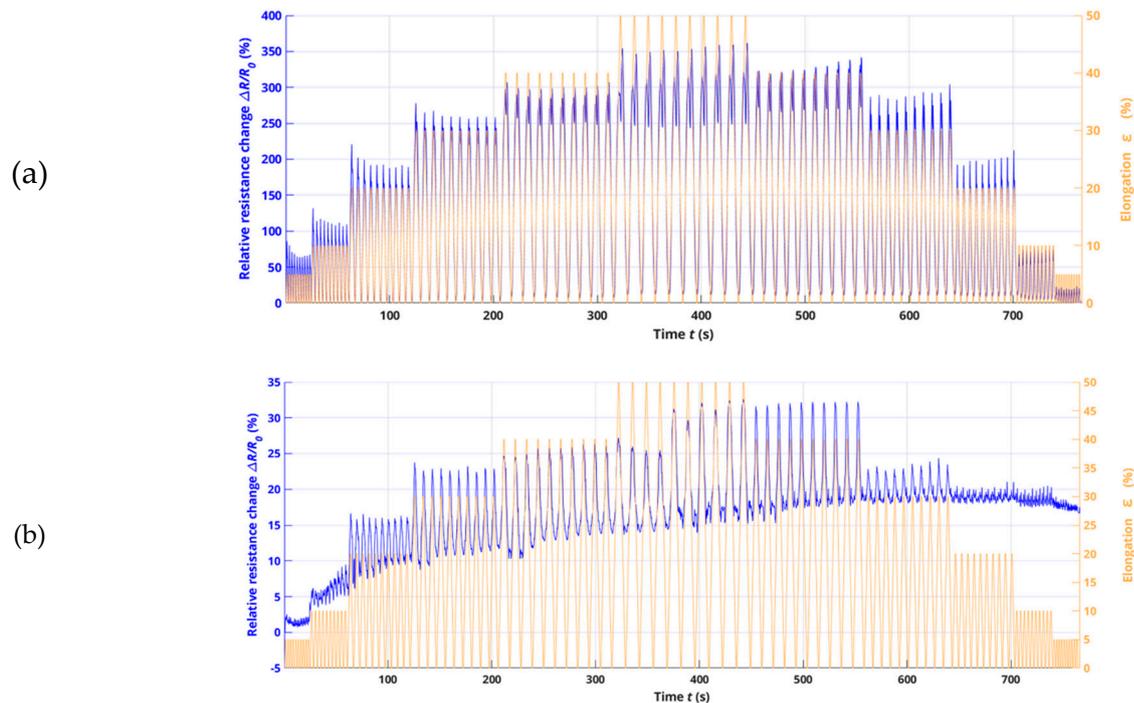
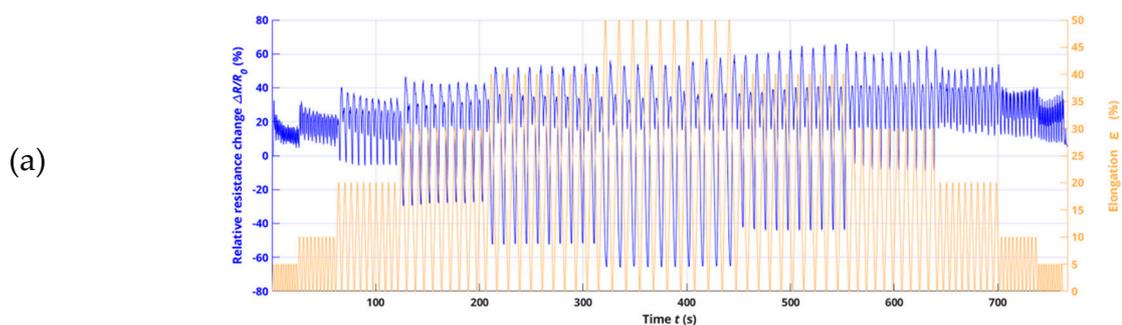


Figure 3. The correlation between strain and resistance over time of (a) W_RL_2x200 and (b) C_RL_2x200.

The sensor oriented in stitch wale direction shows significantly better correlation between strain limits and relative resistance change. From a purely qualitative point of view, the sensor's performance is promising. The quantification of the sensors' properties will be considered and discussed later. In contrast to W_RL_2x200, the electrical resistance and strain do not correlate, as significantly for the sensors fabricated in stitch course direction and the sensor's apparent drift and hysteresis over time can be seen in Figure 3b. Based on this preliminary investigation, the production direction has a decisive influence on the sensor metrics such as nonlinearity, GF, drift, and hysteresis. The results suggest that the knit pattern in stitch course direction, as showed in Figure 3b, is less suitable for a piezoresistive strain sensor for motion capture. Therefore, the next step is to examine and compare the different pattern variants only in the stitch direction.

3.2. Analyze various pattern and its piezoresistive strain sensors

The analysis is based on the variants W_nn_2x200 (Figures 3a and 4a–c). **Error! Reference source not found.** a W_RL_2x200 and Figure 4b W_RRI_2x20 again show a correlation between electrical resistance and strain, whereas the sensor signal of (a) W_RR_2x200 and (c) W_LL_2x200 drifts over the cycles.



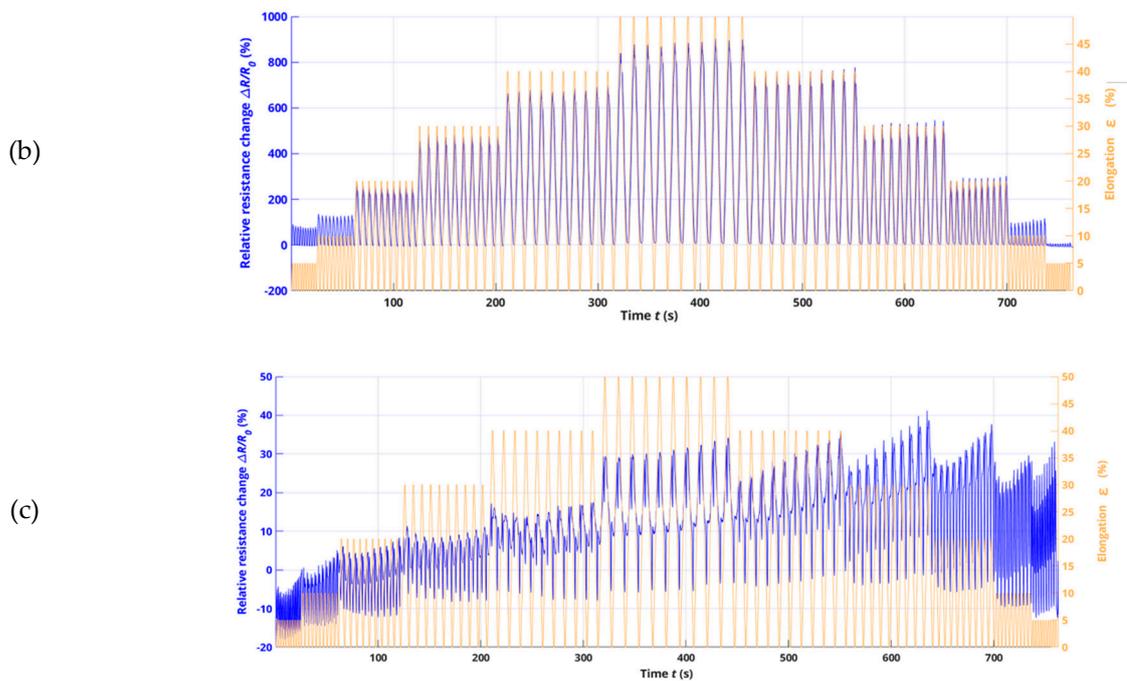


Figure 4. The correlation between strain and resistance over time of (a) W_RR_2x200, (b) W_RRI_2x200 and (c) W_LL_2x200.

The results suggest that the knit pattern also influences the sensor quality and that RL and RRI might be more suitable for a piezoresistive strain sensor for motion capture.

3.3. Analyze of the Nonlinearity, Gauge Factor, Drift, and Hysteresis of various pattern and its piezoresistive strain sensors

Based on these findings, the nonlinearity, GF, drift, and hysteresis are determined in the next step, and the results are presented in the following. Figure 5 illustrates the effect of the knitted pattern and the differences between right-left, right-right, right-right-interlock, and left-left patterns. The effect of sensor width and the differences between one, two, and four meshes in a line are also shortly examined.

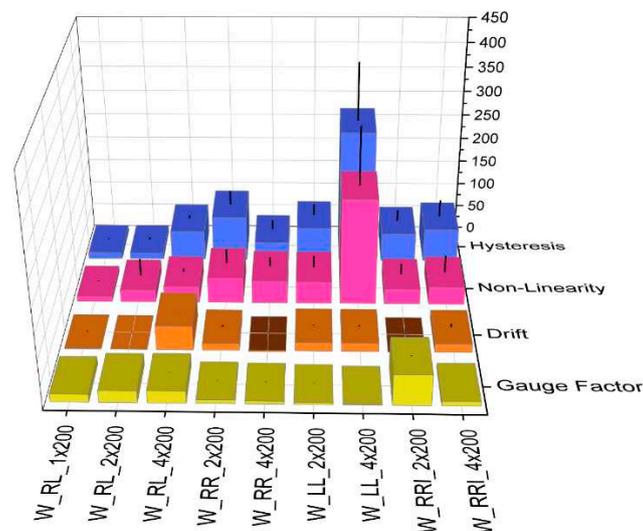


Figure 5. Effect of knitted pattern and the differences between right-left-, right-right-, right-right-interlock- and left-left-pattern and piezoresistive strain sensor width and the differences between one, two and four meshes in line on the sensor performance nonlinearity, gauge factor drift and hysteresis.

Upon examining the nonlinearity, it is evident that variant W_LL_4x200 exhibits a deviation of over 200 %. The same observation applies to hysteresis. However, a clear correlation between pattern, sensor width, and the resulting sensor quality cannot be determined based on these results. On the other hand, the analysis of the correlation between strain and electrical resistance in Figure 4 indicates that the variants LL and RR patterns are unsuitable for the intended purpose. The patterns with the best transmission behavior and the lowest drift are W_RL_4x400, W_RL_2x200, W_RL_1x200, W_RRI_4x200, and W_RRI_2x200. The correlation between strain and resistance over time for the best and the worst versions can be seen for example in the Figure 3a, Figure 4b and in Figure 4c. These samples differ in the RL and RRI patterns and sensor width. The W_RRI_4x200 variant has a GF of 0.9 and a drift of 17 %. The W_RRI_2x200 variant has the highest GF of 6.3 and the lowest drift of 0.15 %. Despite having the same pattern and production direction, the difference can be attributed to the sensor width, which will be further discussed later. The RL pattern with a width of W_RL_4x400 and W_RL_2x200 have a GF of 2.4 and a drift of 50 % and 0.3 % nonlinearity, respectively, while the W_RL_1x200 variant has a GF of 1.6 and a drift of up to 0.8 %. Again, the results differ based on the sensor width rather than the pattern. When considering the sensor width, it can be observed that the variants with four meshes exhibit a nonlinearity of 33.5 % and a hysteresis of 61.5 % for the RL pattern. For the RRI pattern, the values are in a similar range with a nonlinearity of 36 % and a hysteresis of 69 %. Reducing the width to two meshes also reduces the nonlinearity to 25 % and the hysteresis to 12.5 % for the RL pattern. For RRI, the nonlinearity is 31 %, and the hysteresis is 58 %. Despite having a high GF and low drift, the deviations in terms of linearity and hysteresis are more significant for W_RRI_2x200 compared to the RL variants. Although W_RL_1x200 has a lower GF, it exhibits the lowest nonlinearity at 10.7 %.

4. Discussion

Based on the preliminary investigation, the production direction has a decisive influence on the sensor metrics and the C direction is unsuitable as a production direction for a piezoresistive strain sensor. In addition to the production direction, the knit pattern also influences the sensor quality. The results support the hypothesis that LL and RR patterns are unsuitable and that RL and RRI might be more suitable for a piezoresistive strain sensor for motion capture, as indicated by the correlation between strain and resistance change in Figure 4. Based on Figure 5 it can be assumed that the LL and the RR pattern might be more unsuitable for a piezoresistive strain sensor because the GF is lower than 0,8 %. In comparison with all four characteristics, it can be summarized that the pattern LL and RR might be less suitable pattern for a piezoresistive strain sensor with reliable properties. The mesh tops are always alternate above or below the mesh bottoms in an LL pattern (Figure 6).

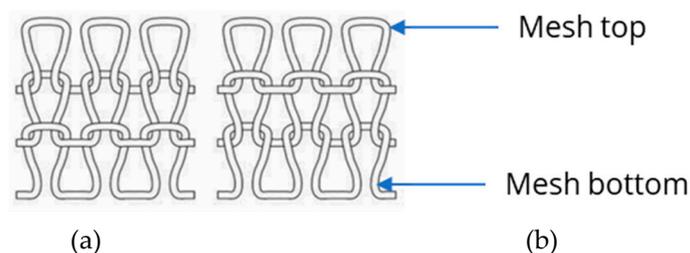


Figure 6. LL pattern with face side (a) and back side (b) [32].

The alternation between the contact points of the mesh tops and bottoms in the sensor might lead to an indifferent change in resistance when stretched since the mechanical strain and, thus, the electrical resistance has probably a different effect on a crossing point lying above the mesh than on one lying below. As the sensor geometry changes due to strain, the connection points within the sensor also vary, resulting in fluctuations in sensor performance.

In RR pattern (see Figure 7), the mesh top and bottom interlock in the same way as in RL pattern (see Figure 8), with the difference that the meshes are knitted on two needle beds, and the front mesh

is continuously interlocked with the back mesh. In this way, the stitch wales from the front and back needle beds always alternate, resulting in a knit with twice as many meshes as in RL.

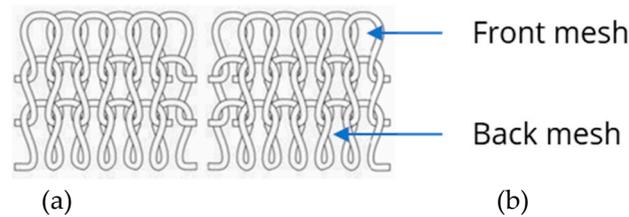


Figure 7. RR pattern with front, back meshes, face side (a) and back side (b) [32].

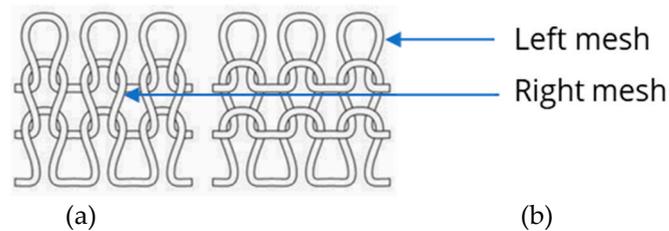


Figure 8. RL pattern showing left and right meshes with face side (a) and back side (b) [32].

Therefore, it would be expected that a RR pattern would behave the same way as the RL knit. In both patterns, it can be seen only right meshes on the right side and left meshes on the left side. Because the mesh bottom and mesh top always interlock, the sensor has a high degree of stretch and good transmission behavior, especially with the RL knit. However, twice the number of meshes results in a minor change in sensor geometry and resistance change at the same strain, which leads to poor transmission behavior GF of the sensor.

The results show that the two variants W_RL_1x200 and W_RRI_2x200 have a reliable sensor performance but difference in nonlinearity and hysteresis. The distinction between the two pattern variants is due to the interlocking points between mesh tops and

-bottoms. In RRI, the interlocking is always offset by one mesh diagonally (see Figure 9b), resulting in more significant deviations in electrical resistance within the sensor during stretching in contrast to the RL. In the RL knit, there is only one row of meshes (Figure 9a), and as already described above, the mesh top and bottom are always in contact without interlocking.

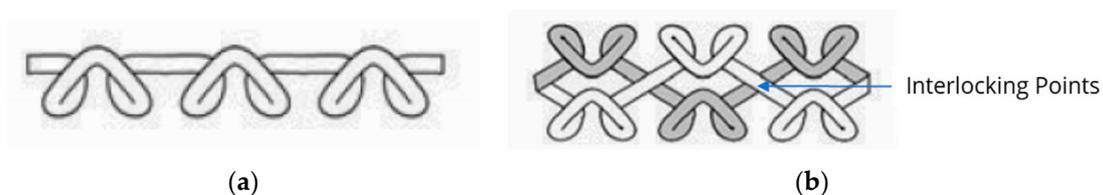


Figure 9. Top view of RL pattern (a) and the top view of RRI showing the diagonally interlocking points (b) [32].

In Addition to the interlocking points, the sensor of the RRI pattern consists of twice as much material as the RL pattern.

The results obtained in this research significantly contribute to the state of the art and tie in directly with the summarized findings from the Introduction. As discussed, the influence of knitted patterns like right-left, left-left, or interlocked ones on the sensor performance still needs to be investigated. Nevertheless, in this systematic study, the influence of the different pattern are discussed, and differences concerning the sensor behavior could be elaborated. It was also established that the production direction impacts selecting the correct sensor design. At least the electro-mechanical properties of strain sensors under multi-cyclic mechanical deformation and thereby verified their suitability as strain sensors for motion capture a. o. in medical applications were

investigated. It was found that the knitted sensors showed reliable sensor behavior even under high cyclic loading and would be suitable for long-term use under different stresses.

5. Conclusions

In summary, the W_RL_1x200 and W_RRI_2x200 variants are the piezoresistive strain sensors with the highest sensor performance and might be ideal for use in smart textiles for medical applications. For selecting the appropriate knitted sensor, it is necessary to compare all four properties and weigh which parameters need to be fulfilled in each dimension and which ones can be somewhat neglected. Ultimately, right-left and right-right-interlock patterns are most suitable knitted structures for a piezoresistive strain sensor, with RRI exhibiting higher nonlinearity and hysteresis than RL. However, the width of the sensor is more crucial for sensor quality. A sensor width of four results in lower sensor quality regardless of the pattern, while width two for RRI and width one for RL are the best variants considering all four quality criteria. Unanswered questions remain regarding why adding one or two mesh significantly affects the sensor's performance. Additionally, it remains open within the study why the production direction causes such a sensor drift. For this reason, further studies are needed to investigate what influence the sensors width and the production direction has. The knowledge about these sensors' properties is necessary to design and manufacture different piezoresistive strain sensors to meet the requirements of various medical applications. The findings of this study contribute to the ongoing research and development efforts in the field of smart textiles, particularly in the domain of medical applications.

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