

Characterisation of low-cost stretchable strain sensors for wearable devices

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Abstract

This paper presents the characterisation of the three distinct materials considered to be used as a resistance-type strained-based sensor on a wearable device. Other performance parameters besides the usual linearity, sensitivity, working range, and hysteresis were also considered. These included the resistance variations caused by a changing temperature, the effects of moisture on the sensor's resistance, and the stress coefficient of resistance. These were necessitated by the nature of the operational environment of most wearable sensors, which may entail the heat introduced to the sensor due to its proximity to the human body, the moisture from perspiration and the limited amount of force that a feeble patient say, can be able to exercise on the sensor. The selected sensor had a high degree of linearity, as established using the linear regression model ($R^2 = 0.94$), had a decent sensitivity (gauge factor = 1.7), a working range of at least 30% strain, and suffered insignificant hysteresis (6.3%). This sensor also had a moderate stress coefficient of resistance (0.11%/KPa) and was unaffected by the changes in temperature and moisture. And the best part is that it is also low-cost.

Keywords

e-textiles, gauge factor, stress coefficient of resistance, temperature coefficient of resistance, wearable device

1. Introduction

Recent technological advances enabling smart wearable healthcare and long-term and remote health monitoring, such as the Internet of Things, artificial intelligence, the Metaverse, and 5G mobile communication, have created a high demand for high-performance biosensors and e-textiles [1–7]. Apart from the biosensor meeting the performance requirements, the sensors should also be readily available and low-cost to make them applicable to developing countries.

At the heart of every Biosensor is a sensing element, which is essentially a physicochemical transducer that

may be optical, piezoresistive, piezoelectric, or electro-mechanical that detects and converts a biological signal such as pressure, pH, or body heat into a digitally recognisable and measurable signal such as current or voltage [8, 9]. Some examples of the innovations include the optical-based sensors [10–16], the piezoresistive [17–20] and the piezoelectric ones [21–25].

However, wearable strain sensors have been of keen interest because of their diverse applications in personalised health monitoring, human motion detection, and human-machine interfaces [26–28].

Strain sensors transduce mechanical deformations into electrical signals. The two main types are resistance and

capacitive strain sensors [29]. The former has a slight edge over the latter as those typically tend to have a higher gauge factor, have a better form factor (for integration onto textiles or skin), have a better anti-interference ability, have better stretchability, and are overall more affordable to implement [30–32].

This paper presents the performance considerations, the experiments undertaken in investigating these considerations, and the results obtained from the said experiments when deciding the most suitable resistive-type strain sensor from amongst three discreet sensor samples. Although plenty of works have reported such evaluations [32–38], what sets this work apart is the details it goes into when assessing other characteristics that are hardly mentioned in these previous works, such as the Stress Coefficient of resistance, the effects of other confounding factors such as moisture and temperature fluctuations.

2. Material and methods

Resistive-type sensors are typically composed of electrically conductive sensing films such as silver nanowires or graphite integrated with a flexible material such as rubber. When composite structures are stretched, microstructural changes in the sensing films lead to a change in electrical resistance as a function of the applied strain. After the release of the strain, realignment of the sensing films to their original states recovers the electrical resistance of sensors, albeit sometimes not perfectly so [39, 40].

All the sensors considered in this paper are materials whose electrical resistance alters when a strain is applied. The sensors' properties are summarised in Table 1 below.

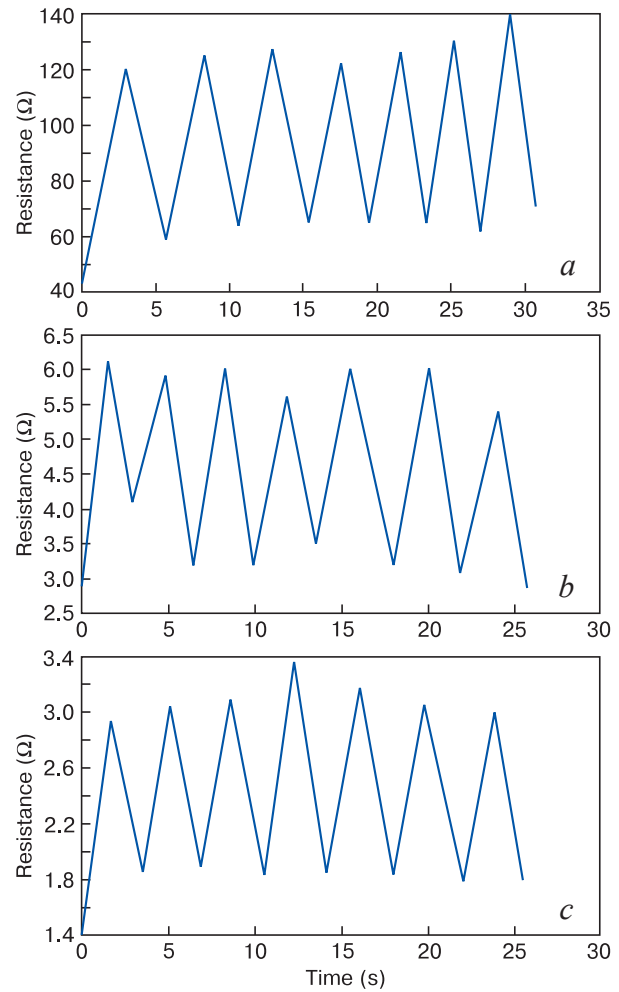
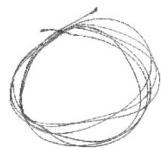


Figure 1. Resistance against time profiles during 7 stretch cycles for: (a) sensor 1; (b) sensor 2; (c) sensor 3

Table 1. The properties of the sensor samples under consideration

Sensor ID number*	Sensor name**	Composite material	Unstretched length (m)	Unstretched resistance (Ω)	Cross-sectional area (m ²)	Image
1	Thread	Cotton and nano plated with silver	$1.15 \cdot 10^{-1}$	42	$2.0 \cdot 10^{-7}$	
2	Fabric	Silver-plated, knitted nylon and elastomer	$2.2 \cdot 10^{-2}$	4	$1.4 \cdot 10^{-5}$	
3	Rubber	Carbon-black Impregnated Rubber	$5.5 \cdot 10^{-2}$	650	$3.1 \cdot 10^{-6}$	

Note: * The sensor number will be what is used to identify each of the sensors in remainder of the document. ** The sensor names are neither the technical nor the manufacturer's issued names, but rather an arbitrary identification that best distinguished the sensors for the authors' convenience.

From the composite material, one may conclude that all these strain-based sensors are flexible, lightweight, and durable. An essential attribute of these sensors for their intended use is that they do not suffer from permanent distortion after being strained. This is demonstrated by the Resistance vs. Time graphs that show the “resistance profile” after subjecting the sensors to seven-cycle tensile testing, as illustrated in Fig. 1 below.

It was noted that all these graphs also demonstrate what other authors, such as [41, 42] and [43], have previously reported, and that is the unstretched resistance in the first cycle is significantly lower than that of the subsequent cycles, wherein it becomes relatively more stable.

These graphs also show that sensor 1 has the most significant response time. While sensor 2 and sensor 3 have approximately the same response time. This phenomenon, the authors speculate, most likely has something to do with the fact that the thread-based sensor has the most considerable absolute change in resistance.

2.1. Experimental details

This study's primary objective was establishing the most suitable strain-based sensor between the three options. In this context, the ideal material is the one that has a good stretch ability as well as superior electrical performance.

The resistance should vary relatively linearly with the strain (stretch) of the sensor. Additionally, external factors such as temperature and moisture should not affect its precision.

2.2. Experimental setup

The first and most important relationship that the authors investigated was that of electrical resistance against the sensors' strain. The typical design for this investigation is to use a variation of a tensile Instron device as given in other works [41, 44, 45]. The basic idea of a tensile test is to place a sample of a material between two fixtures called "grips", which clamp the material of known dimensions. An incremental load is applied to the material gripped at one end while the other is fixed. The change in length (strain) of the sample is simultaneously measured. Some examples of such equipment are given in Fig. 2 below.

However, this setup costs a small fortune and is somewhat of a rare find in this part of the world. Fortunately, in the absence of one, and for investigating the stretch caused by small loads, this experimental setup could be recreated with the run-of-the-mill physics laboratory apparatus as done in works such as [2]. This setup is shown in Fig. 3 below.

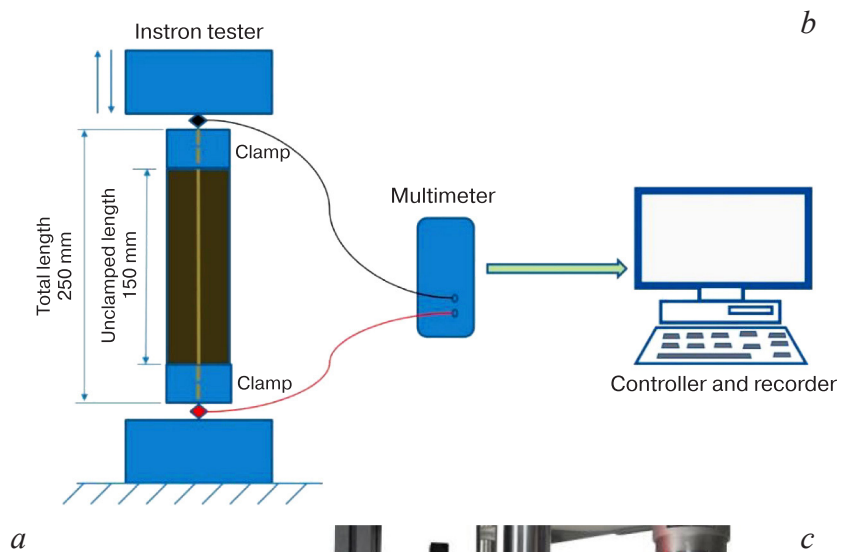
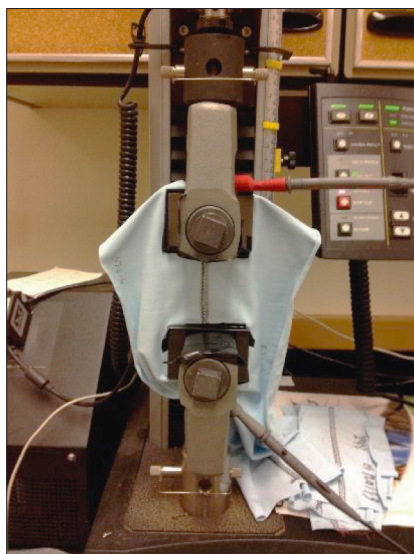


Figure 2. The typical setup for Instron tensile tester as given by: (a) in [41]; (b) in [41]; and (c) in [44]

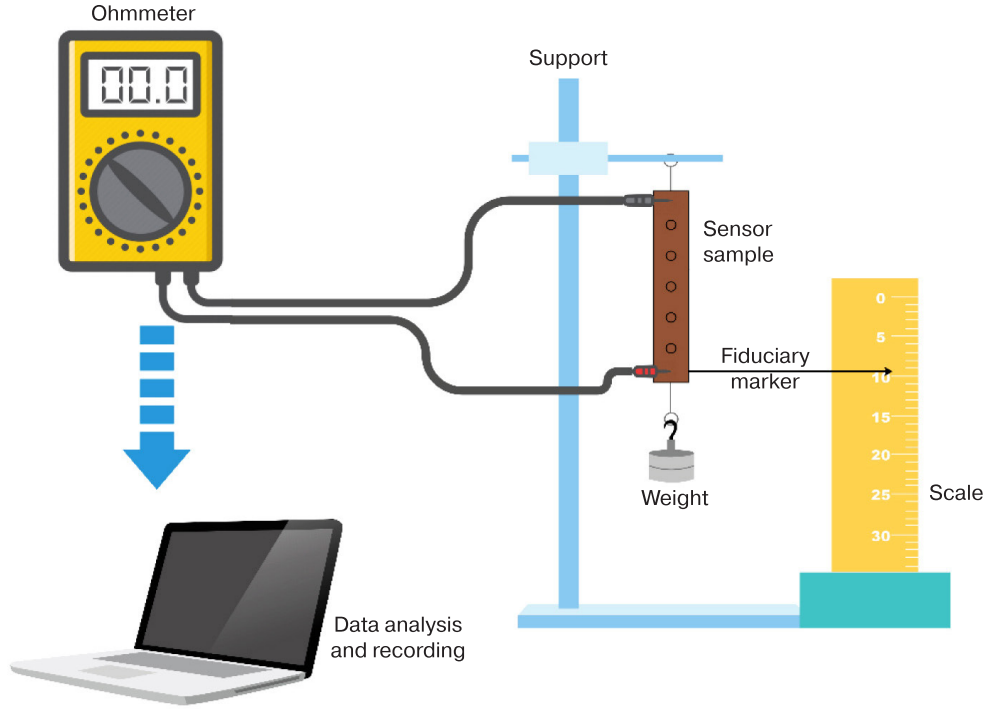


Figure 3. Experimental setup used to measure the effect of strain on resistance used in this work

The change in length of the sensor was recorded against the change in resistance for both the loading and unloading phases.

From this setup, the results of the sensors' specimen change in electrical resistance against strain were found.

3. Theory

3.1. Performance considerations

The performance considerations under investigation for these sensors include those put forward by authors such as Amjadi M. et al. [29]. These are sensitivity, linearity, working range and hysteresis.

Apart from these commonly investigated parameters, this work investigated other confounding factors, namely temperature changes and moisture effects.

These considerations are summarised below.

3.1.1. Sensitivity

The central aspect of the sensitivity of the sensors that is under investigation is known as the *Strain Sensitivity Coefficient*, commonly known as the *Gauge Factor* (k_ϵ). It is given by:

$$k_\epsilon = \frac{\left(\frac{\Delta R}{R_0} \right)}{\left(\frac{\Delta l}{l_0} \right)}, \quad (1)$$

where R_0 and l_0 are the unstretched resistance and unstretched length, respectively, while ΔR is the value of resistance change for a change in length (a stretch) of Δl .

The ratio of the increase in length to the original length $\Delta l/l_0$ is commonly referred to as the *Strain*, given by ϵ .

Therefore Eq. (1) above can be written as:

$$k_\epsilon = \frac{\left(\frac{\Delta R}{R_0} \right)}{\epsilon}. \quad (2)$$

The gauge factor, a dimensionless quantity, can be found by calculating the gradient of the characteristic curve on a graph of resistance change against strain. The ideal sensor would have the most significant gauge factor, meaning it has a high sensitivity to strain. This would make it better at detecting slight changes in strain as these would show significant changes in resistance, increasing the precision of the strain-based sensor [46].

Another sensitivity dimension seldom discussed when analysing the suitability of strain-based sensors is the *Stress Sensitivity Coefficient* (k_σ). It measures the force per unit area of the sensor required to cause a resulting resistance change [47]. It is given by:

$$k_\sigma = \frac{\left(\frac{\Delta R}{R_0} \right)}{\left(\frac{F}{A} \right)}, \quad (3)$$

where R_0 is the initial resistance before applying any load, ΔR is the resistance change caused by a certain amount of load applied per unit cross-sectional area. F and A are the

loads applied to the sensor sample and the sensor sample's cross-sectional area, respectively. The force per unit area, F/A is called the *Stress* (σ). Therefore, Eq. (3) above can be written as:

$$k_{\sigma} = \frac{\left(\frac{\Delta R}{R_0} \right)}{\sigma}. \quad (4)$$

If the force is in Newtons (N) and the Cross-Sectional Area is in square meters (m^2), then the units for σ are given in Newtons per Square meter (N/m^2) or Pascals (Pa), Where $1 N/m^2 = 1 Pa$. Therefore, the units for k_{σ} are “per pascal” (Pa^{-1}). For this work, the sensor with the more significant value of k_{σ} was preferred because of its more diverse applications – the sensor gives a large resistance output for a small value of stress.

The experimental setup used for finding k_{ϵ} and k_{σ} is already shown in Fig. 3 above.

3.1.2. Linearity

Linearity refers to the sensor's ability to exhibit a consistent and proportional change in resistance with increased strain. Ideally, a perfect sensor would show a straight-line relationship on a graph of resistance against strain, indicating that the resistance changes linearly with strain. However, as authors such as [48, 49] have already reported, most resistance-based strain sensors suffer from non-linearity, if only for a specific strain range.

The nonlinearity of sensors makes their calibration process significantly more complicated, time-consuming, and costly. It also leads to reduced precision and resolution and makes overall system integration difficult, requiring additional circuitry, signal conditioning and sophisticated algorithms [29].

To find the Linear portion of the sensors under testing, the *linear fit* was found by computing the linear regression of the first order of the averaged values of the loading and unloading phases of the sensors. The “fitness” of this linear fit was confirmed in each case by visual inspection and calculating the Coefficient of Determination (R^2). The relationship between the change in resistance and strain was only considered linear for the strain range of values when R^2 was significantly large ($R^2 \geq 0.9$). This region was considered the *Working Range* of the sensor.

3.1.3. Working range

Resistive-type strain sensors with a wide working range are preferred because they can measure a broader spectrum of strain input values, allowing them to be used in diverse applications. They also tend to be more cost-effective, as using a single sensor with a wide range is better than procuring, installing, and maintaining multiple sensors to cover different measurement ranges.

In some cases, a more prominent gauge factor may limit the range of strain that can be accurately measured [50]. In such instances, the relationship between the change in resistance and the strain tends to become non-linear after applying a certain amount of strain. This behaviour is

typical of strain-based resistive sensors, as demonstrated by the works of authors such as [51–53]. For the context of this work, the working range was the portion of the graph in which the resistance change and the change in strain were proportional.

While evaluating these three sensors, the preferred sensor would have a wider working range.

3.1.4. Hysteresis

The hysteresis of a resistive-type strain sensor is the phenomenon where the output electrical resistance of the sensor for a given strain on the loading cycle is not equal to the electrical resistance for that same strain on the unloading cycle [54]. Ideally, the sensor would have the same resistance at that strain point regardless of whether it is loading or unloading, so one strain value can always be measured with one resistance value without knowing which cycle the sensor is in.

The hysteresis, represented by γ_H , can be given as a percentage given by:

$$\gamma_H = \frac{A_L - A_U}{A_L} \times 100, \quad (5)$$

where A_L and A_U are the areas of the Loading and Unloading characteristic curves, respectively.

When this equation cannot be used to find the value of hysteresis, one could approximate the sensor with the most prominent hysteresis by visual inspection. This is especially the case when comparing the hystereses of a limited number of sensors. The sensor whose resistance-strain graph has the most significant deviation from the characteristic curve has the most considerable hysteresis and vice-versa.

The hysteresis of a resistance-type strain sensor can be attributed to various factors, including material properties, mechanical design, and manufacturing processes. Works such as those by [55–57] go into a detailed investigation concerning this, whereas [58, 59] discuss some of the possible means, at least through fabrication considerations, to mitigate this.

A large hysteresis is undesirable because it can introduce errors in strain measurements by reducing the sensors' accuracy, reliability, and stability, especially when the strain is applied cyclically or in dynamic applications [2]. Therefore, in this work, a sensor with a small hysteresis was preferred to one with a large hysteresis.

All these tests mentioned above were performed at room temperature.

3.2. Other confounding factors

The final factors to be investigated were temperature and moisture and how they might affect the resistance output of the sensors.

3.2.1. Thermal stability

Usually, strain-based sensors are tested and calibrated at room temperature (approx. 20 °C to 25 °C), or authors

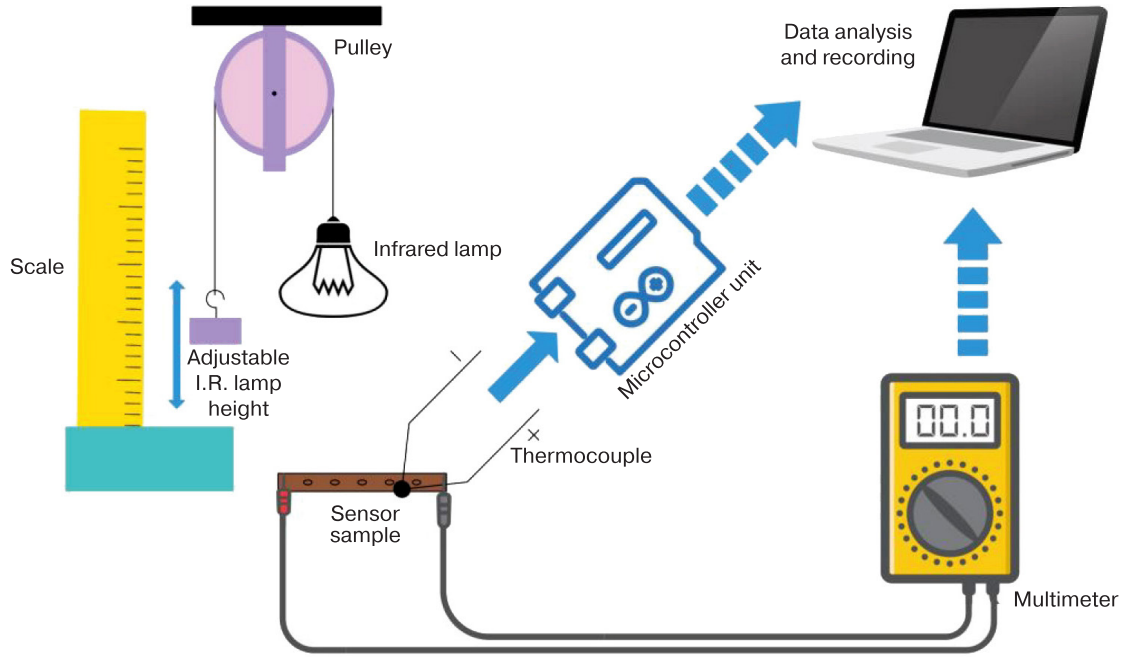


Figure 4. The experimental setup for thermal ascent

are completely mute about that aspect in their works. However, the intended end use for sensors was for wearable devices on a human body with a core temperature of around 36.5 °C or much higher than that in infants or when an adult patient is febrile [60]. Furthermore, some resistance-based strain sensors have been reported to increase in temperature over time as current passes through them in a process called self-heating caused by the excitation voltage [61, 62]. The work by [63, 64] concludes that temperature variations may introduce errors in resistance-strain readings if not appropriately compensated for.

This work investigated the relationship between temperature and electrical resistance output for each of the sensors at their unstretched length and Load of 0.0N.

In this investigation, the temperature was varied from approx. 0 °C to about 65 °C. This temperature range was of interest as the operation temperature range (for wearable devices) is well within this range, even after accounting for the temperature increase that has been associated with some resistance-based strain sensors mentioned earlier.

The varying temperatures were measured by a *K*-type thermocouple (nickel–chromium–Nisil), with a range from –20 °C to 1000 °C, a resolution of 1 °C and an accuracy and count of $\pm(1.0\%+5)$.

The thermic ascent to the sensors was caused and controlled by altering the height of an infrared lamp above the sensors, as shown in Fig. 4 below. It was inspired by the setup in the work by [64].

The relationship between temperature and resistance is called the *Temperature Coefficient of Resistance* (TCR), represented by α_t . The TCR indicates how much the resistance of a sensor changes with respect to temperature [65]. For a temperature range that is not too great,

this variation can be represented approximately as a linear relation:

$$R_T = R_{T_0}[1 + \alpha_T (T - T_0)], \quad (6)$$

where R_T and R_{T_0} are the resistances at temperatures of T and T_0 , respectively. T_0 is often taken as room temperature or 0 °C. Rearranging Eq. (6) above gives:

$$\frac{R_T - R_{T_0}}{R_0} = \alpha_T (T - T_0). \quad (7)$$

Which can also be presented as:

$$\frac{\Delta R}{R_{T_0}} = \alpha_T \Delta T, \quad (8)$$

where ΔR is the resistance change of the sensor due to a temperature change of ΔT . This means that from a graph plotted of $\Delta R/R_{T_0}$ against ΔT , the gradient will give the Thermal Coefficient of Resistance.

To confirm that the resistance change correlated to temperature change, the authors recorded, plotted, and compared the values for resistance when the temperature was being increased from minimum to maximum with those when the temperature was being decreased in the reverse order. The cooling of the sensors was done by placing each of the sensors' samples in turn atop a generic 12706 thermoelectric cooling module that makes use of the Peltier principal to actively cool the temperature of one side of its two plates to as low as –30 °C [66, 67].

The sensor with the most negligible absolute Temperature Coefficient of Resistance is a more desirable one as it indicates that the sensor has greater thermal stability, meaning it exhibits minimal electrical resistance changes with temperature variations. This stability allows for more accurate and reliable temperature measurements

over a wide range of temperatures. It also means less design and calibration considerations must be put towards temperature compensation when integrating the sensor for most real-world applications.

3.2.2. Moisture effects

Although the effects of moisture on resistive-type strain sensors have been thoroughly investigated in works such as [68–73], in this body of work the authors will compare the differences in the Resistance change vs. Strain graphs for the wet, irrigated sensor, versus one that is dry (at a relative humidity of between 20 to 50%) to identify the sensor who's resistance output might be affected the most by the various moisture for reasons already highlighted in works such as [74], i.e. how water molecules may sometimes act as an electrolyte and introduce conductive pathways.

This was an important aspect to investigate as the end use of the sensor will be as a wearable device and things such as human sweat tend to occur, not to mention the relative humidity that spontaneously may rise in the atmosphere from time to time. The sensor with the Change in Resistance vs. Strain that varies the least (ideally identical to) when the sensor is subject to moisture vs. when under dry conditions may be considered the most desirable.

4. Results and discussion

According to the presented results in Fig. 5, the following could be ascertained: sensor 1 had the greatest k_ϵ (4.5), whilst sensor 2 and sensor 3 had similar gauge factors of about 1.7. This gauge factor is not too far off from that found in other works such as [75–78]. However, sensor 3 had the most extensive working range of all three, with at least 30% strain, compared to sensor 2, which had slightly more than half of that.

It shall remain inconclusive for this work whether the working range of sensor 3 is much more extensive than the one presented. This is because the authors stopped applying the strain, not because the stretch limit was reached, as was the case for sensor 1 and sensor 2, but rather because the authors were very conservative in their stretch for sensor 3 out of fear of exceeding the elastic limit or breaking the sensor sample.

For sensor 1, the resistance change due to the applied strain starts to gradually taper off past the working range, whilst that for sensor 2 becomes negative past the Linear Region Limit.

A summary of the test results obtained from some sensors in recently reported works, along with those found for the sensors under testing in this paper, are given in Table 2.

Apart from the geometrical differences between the sensors highlighted in Table 1, the differences in these and other performance parameters discussed below can be attributed to the different strain-responsive mechanisms

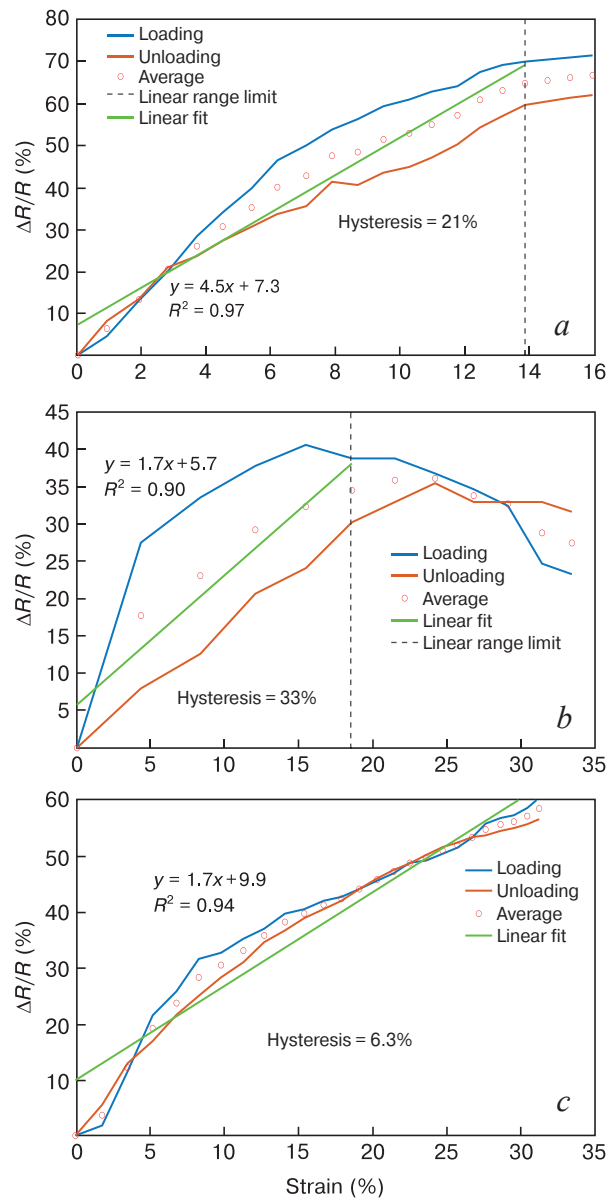


Figure 5. The resistance change against strain graphs for (a) sensor 1, (b) sensor 2, and (c) sensor 3 at room temperature

of each sensor. These include but are not limited to the piezoresistive effect [79–85], the disconnection mechanism [86, 87], crack propagation [88, 89] and the tunneling effect [90, 91].

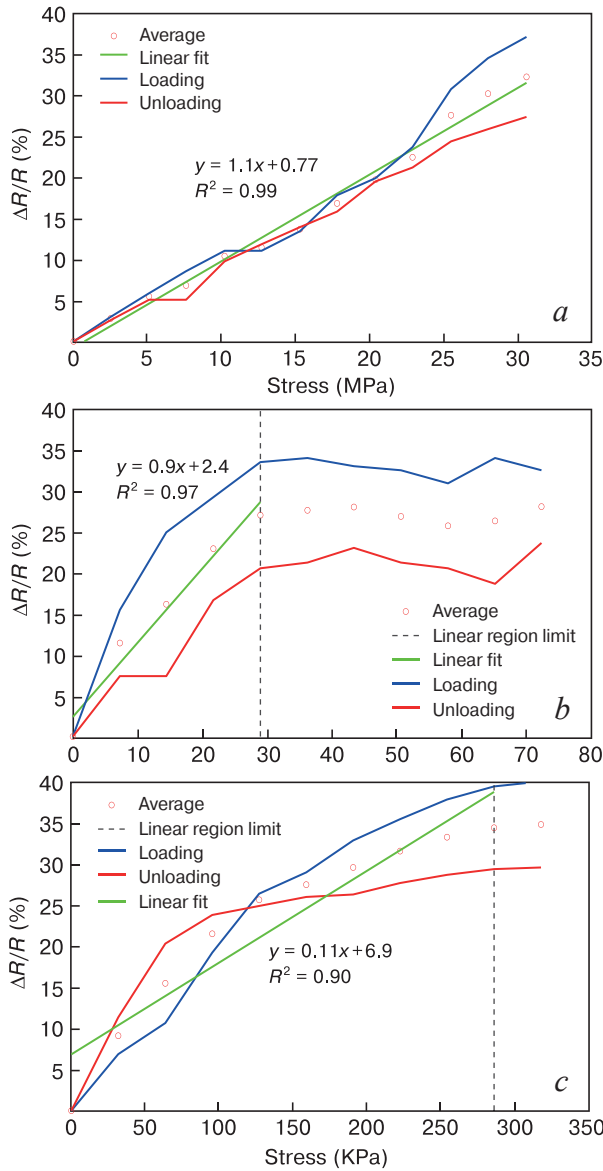
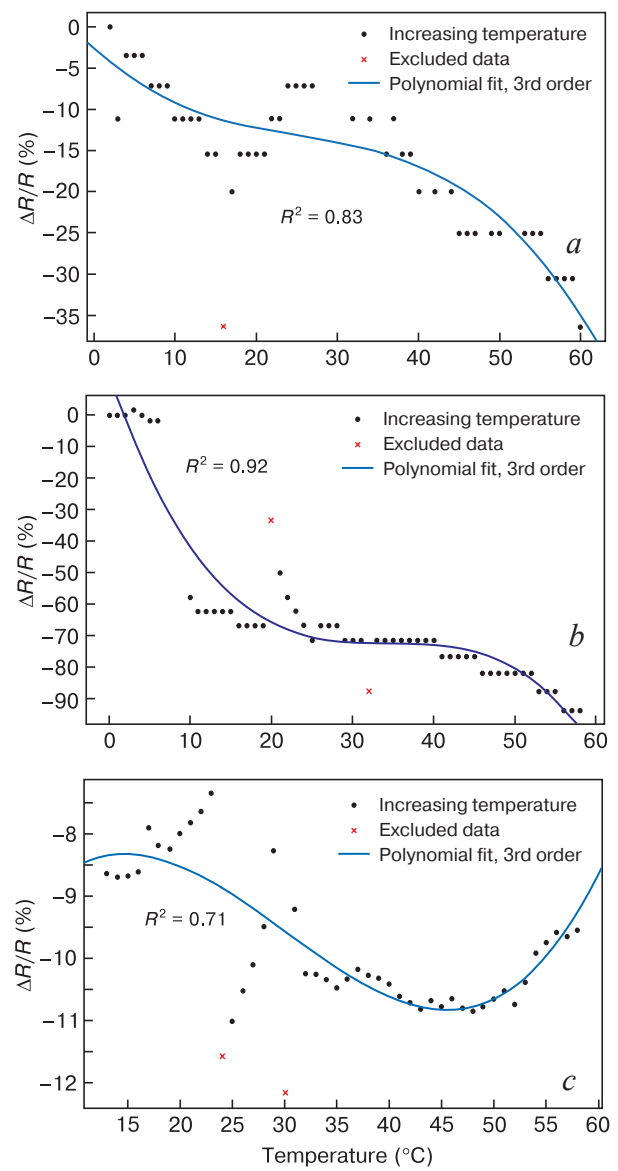
The results in Fig. 6 show that sensor 1 had the smallest k_σ of 1.1 %/MPa, followed by sensor 3, which has a stress coefficient of resistance of about 0.11 %/KPa and finally sensor 2, which has a k_σ of almost 1%/KPa. This means that sensor 2 is the one that requires the least amount of force to generate a unit of resistance change.

The Resistance against Temperature relationships for all the sensors were concluded to most approximate a non-linear relationship, given by a third-order polynomial. This is shown in Fig. 7. Such a profile has long been validated for some semiconductor material such as NTC thermistors in [98, 99] sensor 2 was the most affected by temperature fluctuations, with the greatest resistance

Table 2. A comparison of the tested sensors to those that have been recently reported by other authors

Reference	Materials	Working range (%)	Gauge factor	Hysteresis (%)
[92]	AgNW/PDMS	70	2–14	~28
[93]	PDMS/CNF	70	6.5	~14.3
[77]	CNTs/ Ecoflex	500	1–2.5	N/A
[94]	CB/PDMS	10	1.8–5.5	N/A
[95]	PPy/SR	100	1.7	7.89
[96]	Carbon grease	100	3.8	~10
[97]	Mo/PBTPA	5	20	~11
[2]	SSCC	100	13.8	6.2
This work (sensor 1)	Cotton/AgNW	~14	4.5	21
This work (sensor 2)	Nylon /AgNW/ Elastomer	~30	1.7	33
This work (sensor 3)	CB/Latex	≥30	1.7	6.3

Note: AgNW – silver nanowire; PDMS – polydimethylsiloxane; CNF – cellulose nanofiber; CNTs – carbon nanotubes; CB – carbon black; PPy – polypyrrole; SR – silicon rubber; Mo – molybdenum; PBDTA – polybutanedithiol; SSCC – stretchable strain segregating conductive composite.

**Figure 6.** The resistance change vs. stress graphs for (a) sensor 1, (b) sensor 2 and (c) sensor 3 at room temperature**Figure 7.** The change in resistance vs. temperature graphs for (a) sensor 1, (b) sensor 2 and (c) sensor 3

change towards the lower fixed point and a relatively stable resistance between the usable temperature ranges of between 20 °C and 40 °C. Sensor 1 was another one whose change in resistance was significantly affected by temperature, with the resistance change varying approximately 35% between the measured temperature range. Both sensor 1 and sensor 2 had a negative temperature coefficient, meaning that the change in resistance decreased, with an increase in temperature. Finally, sensor 3 exhibited no significant resistance change in relation to the temperature change, for the given temperature range.

Figure 8 shows that the effect of moisture on all these Sensors was negligible, at least as far as the sensitivity was concerned. However, for sensor 2 there was a significant and positive increase in the working range of the sensor from about 17% strain when dry to about 28% strain after it had been irrigated.

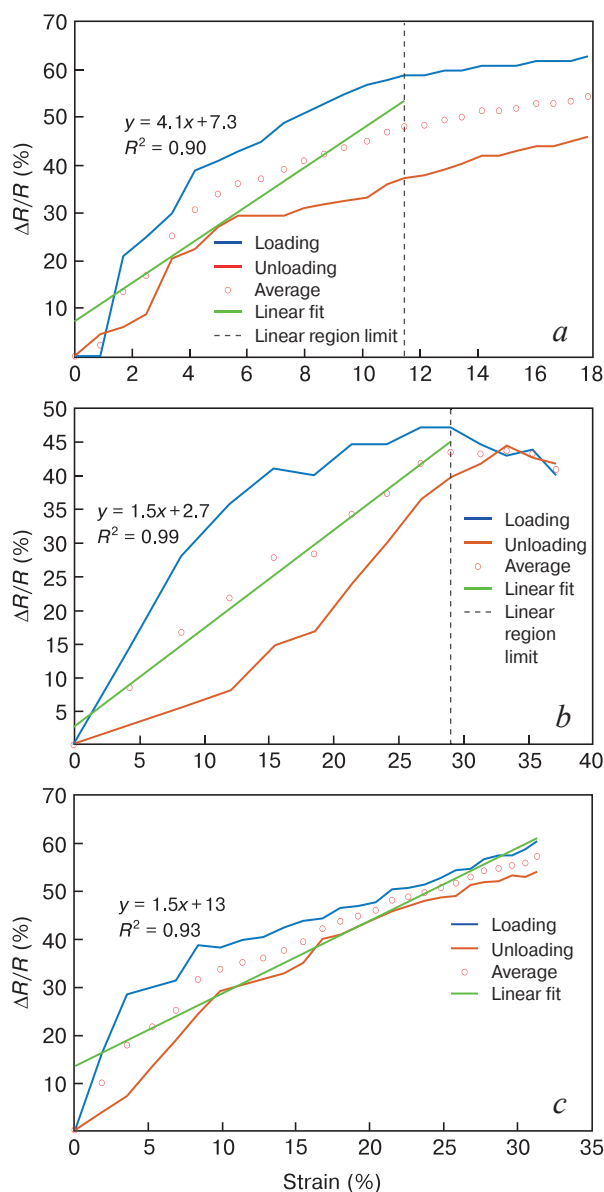


Figure 8. The graphs of change in temperature vs strain for the irrigated sensor samples: (a) sensor 1, (b) sensor 2 and (c) sensor 3

5. Conclusions

After a series of tests that weighed out all the above-stated performance considerations, the resistance-based strain-based sensor that was finally selected was sensor 3. This is because while it exhibited a relatively low gauge factor (1.7), and has a moderate stress coefficient of resistivity (0.11 %/KPa), it has the best linearity of all the sensors, has the largest working range ($\geq 30\%$), and is virtually immune to temperature fluctuations. The sensor is also low-cost ($<< \text{USD } 10$) per sample.

Although sensor 3 was the sensor of choice for this specific application and situation, it should be noted that other impressive qualities that Sensor 1 and Sensor 2 possessed such as having the highest k_e (4.5) and k_σ (0.90 %/KPa) respectively would make them ideal for other applications, in which these traits are the priority. Because of the work done in this paper in investigating each of their performance attributes, it means the authors will efficiently select a sensor of known and predictable behaviour and performance during such a time.

In the future, the authors intend to investigate how the sensor's performance degrades with cyclical use over time. Furthermore, the authors intend to discuss the final application of the sensor, its calibration and its realisation on a voltage divider circuit or Wheatstone bridge circuit as the resistor-varying element. This stretch sensing element is to be used as a wearable device, a real-time respiration detection and monitoring device to be implemented on an existing prototype of a rapidly manufactured, low-cost ventilator in the university's Department of Electrical Engineering of the University of Botswana.

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Availability of data and materials

The data generated from this work can be shared by the corresponding author upon a reasonable request.

Competing interests

The authors declare that they have no competing interests.

CRedit authorship contribution statement

Moses Tazvivona Njovana: Methodology, Formal analysis, Investigation, Writing-Original Draft. **Monageng Kgwadi:** Conceptualization, Supervision. **Sajid Mubashir Sheikh:** Writing-Review & Editing, Supervision.

References

1. Sikandar A., Abdullah, Armand T.P.T., Athar A., Hussain A., Ali M., Muhammad Y., Joo, M.-I., Kim K.-Ch. Metaverse in healthcare integrated with explainable AI and blockchain: Enabling immersiveness, ensuring trust, and providing patient data security. *Sensors (Basel)*. 2023; 23(2): 565. <https://doi.org/10.3390/S23020565>
2. Yoshida A., Wang Y.-F., Sekine T., Takeda Y., Kumaki D., Tokito S. Printed low-hysteresis stretchable strain sensor based on a self-segregating conductive composite. *ACS Applied Engineering Materials*. 2023; 1(1): 50–58. <https://doi.org/10.1021/acsaelm.2c00010>
3. Grant C.F., Srisa-An W., Henshall D.C., Balasubramaniam S. Emerging AI technologies inspiring the next generation of E-textiles. 2023; 14. <https://doi.org/10.48550/arXiv.2303.03205>
4. Meena J.S., Choi S.B., Jung S.B., Kim J.W. Electronic textiles: New age of wearable technology for healthcare and fitness solutions. *Mater Today Bio*. 2023; 19: 100565. <https://doi.org/10.1016/J.MT-BIO.2023.100565>
5. Sun G. The role of textiles in the internet of things. Textile World. August 18, 2022. <https://www.textileworld.com/textile-world/features/2022/08/the-role-of-textiles-in-the-internet-of-things/> (accessed on 22.06.2023).
6. Shafi J., Waheed A. Role of smart wearable in healthcare: Wearable internet of medical things (WIoMT). The IoT and the next revolutions automating the world. 2019. 23 p. <https://doi.org/10.4018/978-1-5225-9246-4.CH009>
7. Devi D.H., Duraisamy K., Armghan A., Alsharari M., Aliqab K., Sorathiya V., Sudipta D., Nasr R. 5G technology in healthcare and wearable devices: A review. *Sensors (Basel)*. 2023; 23(5): 2519. <https://doi.org/10.3390/S23052519>
8. Sharma A., Goud K.Y., Hayat A., Bhand S., Marty J.L. Recent advances in electrochemical-based sensing platforms for aflatoxins detection. *Chemosensors*. 2017; 5(1): 1. <https://doi.org/10.3390/CHEMOSENSORS5010001>
9. Sharma A., Singh A.C., Bacher G., Bhand S. Recent advances in aptamer-based biosensors for detection of antibiotic residues. *Aptamers and Synthetic Antibodies*. 2016; 2(2): 43–54.
10. Yoo W.J., Jang K.W., Seo J.K., Heo J.Y., Moon J.S., Park J.Y., Lee B.S. Development of respiration sensors using plastic optical fiber for respiratory monitoring inside MRI system. *Journal of the Optical Society of Korea*. 2010; 14(3): 235–239. <https://doi.org/10.3807/JOSK.2010.14.3.235>
11. D'Angelo L.T., Weber S., Honda Y., Thiel T., Narbonneau F., Lüth T.C. A system for respiratory motion detection using optical fibers embedded into textiles. In: *Proc. of the 30th annual inter. conf. of the IEEE engineering in medicine and biology society, EMBS'08 – "Personalized Healthcare through Technology"*. Vancouver, BC, Canada; 2008: 3694–3697. <https://doi.org/10.1109/IEMBS.2008.4650011>
12. Arifin A., Agustina N., Dewang S., Idris I., Tahir D. Polymer optical fiber-based respiratory sensors: Various designs and implementations. *Journal of Sensors*. 2019; 2019: 6970708. <https://doi.org/10.1155/2019/6970708>
13. Mathew J., Semenova Y., Farrell G., Akita S., Seki A., Watanabe K. A miniature optical breathing sensor. *Biomedical Optics Express*. 2012; 3(12): 3325–3331. <https://doi.org/10.1364/BOE.3.003325>
14. Krehel M., Wolf M., Boesel L.F., Rossi R.M., Bona G.-L., Scherer L.J. Development of a luminous textile for reflective pulse oximetry measurements. *Biomedical Optics Express*. 2014; 5(8): 2537–2547. <https://doi.org/10.1364/BOE.5.002537>
15. Witt J., Narbonneau F., Schukar M., Krebber K., De Jonckheere J., Jeanne M., Kinet D., Paquet B., Depre A., Tancredi D'Angelo L., Thiel T., Logier R. Medical textiles with embedded fiber optic sensors for monitoring of respiratory movement. *IEEE Sensors Journal*. 2012; 12(1): 246–254. <https://doi.org/10.1109/JSEN.2011.2158416>
16. De Jonckheere J., Jeanne M., Griller A., Weber S., Chaud P., Logier R., Weber J.L. OFSETH: Optical fibre embedded into technical textile for healthcare, an efficient way to monitor patient under magnetic resonance imaging. In: *Proc. Annual inter. conf. of the IEEE engineering in medicine and biology*. Lyon, France; 2007: 3950–39533. <https://doi.org/10.1109/IEMBS.2007.4353198>
17. Massaroni C., Di Tocco J., Lo Presti D., Longo U.G., Miccinilli S., Sterzi S., Formica D., Saccomandi P., Schena E. Smart textile based on piezoresistive sensing elements for respiratory monitoring. *IEEE Sensors Journal*. 2019; 19(17): 7718–7725. <https://doi.org/10.1109/JSEN.2019.2917617>
18. Cay G., Ravichandran V., Saikia M.J., Hoffman L., Laptook A., Padbury J., Salisbury A., Gitelson-Kahn A., Venkatasubramanian K., Shahriari Y., Mankodiya K. An E-textile respiration sensing system for NICU monitoring: design and validation. *Journal of Signal Processing Systems*. 2022; 94(6): 543–557. <https://doi.org/10.1007/S11265-021-01669-9/TABLES/5>
19. De Fazio R., De Vittorio M., Visconti P. A BLE-connected piezoresistive and inertial chest band for remote monitoring of the respiratory activity by an android application: hardware design and software optimization. *Future Internet*. 2022; 14(6): 183. <https://doi.org/10.3390/fi14060183>
20. Raji R.K., Miao X., Wan A., Niu L., Li Y., Boakye A. Knitted piezoresistive smart chest band and its application for respiration patterns assessment. *Journal of Engineered Fibers and Fabrics*. 2019; 14(1): 155892501986847. <https://doi.org/10.1177/1558925019868474>
21. Allataifeh A., Al Ahmad M. Simultaneous piezoelectric noninvasive detection of multiple vital signs. *Scientific Reports*. 2020; 10: 416. <https://doi.org/10.1038/S41598-019-57326-6>
22. Ji Z., Zhang M. Highly sensitive and stretchable piezoelectric strain sensor enabled wearable devices for real-time monitoring of respi-

- ratory and heartbeat simultaneously. *Nanotechnology and Precision Engineering* 2022; 5: 013002. <https://doi.org/10.1063/10.0009365>
23. Klap T., Shinar Z. Using piezoelectric sensor for continuous-contact-free monitoring of heart and respiration rates in real-life hospital settings. *Computing in Cardiology Conference*. 2013; 40: 671–674. <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6713466>
 24. Panahi A., Hassanzadeh A., Moulavi A. Design of a low cost, double triangle, piezoelectric sensor for respiratory monitoring applications. *Sensing and Bio-Sensing Research*. 2020; 30: 100378. <https://doi.org/10.1016/J.SBSR.2020.100378>
 25. Kim Y.G., Song J.H., Hong S., Ahn S.H. Piezoelectric strain sensor with high sensitivity and high stretchability based on kirigami design cutting. *Npj Flexible Electronics*. 2022; 6: 1–8. <https://doi.org/10.1038/s41528-022-00186-4>
 26. Yadav A., Yadav N., Wu Y., RamaKrishna S., Hongyu Z. Wearable strain sensors: state-of-the-art and future applications. *Materials Advance*. 2023; 4(6): 1444–1459. <https://doi.org/10.1039/D2MA00818A>
 27. Ryu S., Lee P., Chou J.B., Xu R., Zhao R., Hart A.J., Kim S.-G. Extremely elastic wearable carbon nanotube fiber strain sensor for monitoring of human motion. *ACS Nano*. 2015; 9(6): 5929–5936. <https://doi.org/10.1021/ACS.NANO.5B00599>
 28. Wang J., Xu J., Chen T., Song L., Zhang Y., Lin Q., Wang M., Wang F., Ma N., Sun L. Wearable human-machine interface based on the self-healing strain sensors array for control interface of unmanned aerial vehicle. *Sensors and Actuators A: Physical*. 2021; 321: 112583. <https://doi.org/10.1016/J.SNA.2021.112583>
 29. Amjadi M., Kyung K.U., Park I., Sitti M. Stretchable, skin-mountable, and wearable strain sensors and their potential applications: a review. *Advanced Functional Materials*. 2016; 26(11): 1678–1698. <https://doi.org/10.1002/adfm.201504755>
 30. Kausar A. *Sensing materials: nanocomposites*. Encyclopedia of sensors and biosensors; 2023. Vol. 2. P. 305–315. <https://doi.org/10.1016/B978-0-12-822548-6.00048-0>
 31. Žlebić Č., Ivanišević N., Kisić M., Blaž N., Menićanin A., Živanov Lj., Damnjanović M. In: *Proc. of the Inter. conf. on microelectronics, ICM. Institute of Electrical and Electronics Engineers Inc. Comparison of resistive and capacitive strain gauge sensors printed on polyimide substrate using ink-jet printing technology. MIEL 2014, Belgrade, Serbia*; 2014. P. 141–144. <https://doi.org/10.1109/MIEL.2014.6842105>
 32. Dong T., Gu Y., Liu T., Pecht M. Resistive and capacitive strain sensors based on customized compliant electrode: Comparison and their wearable applications. *Sensors and Actuators A: Physical*. 2021; 326: 112720. <https://doi.org/10.1016/j.sna.2021.112720>
 33. Lu Y., Biswas M.C., Guo Z., Jeon J.W., Wujcik E.K. Recent developments in bio-monitoring via advanced polymer nanocomposite-based wearable strain sensors. *Biosensors and Bioelectronics*. 2019; 123: 167–177. <https://doi.org/10.1016/J.BIOS.2018.08.037>
 34. Kumbay Y.S., Mutlu R., Alici G. Fabrication and characterisation of highly stretchable elastomeric strain sensors for prosthetic hand applications. *Sensors and Actuators A: Physical*. 2016; 247: 514–521. <https://doi.org/10.1016/J.SNA.2016.06.037>
 35. Mai H., Mutlu R., Tawh C., Alici G., Sencadas V. Ultra-stretchable MWCNT–Ecoflex piezoresistive sensors for human motion detection applications. *Composites Science and Technology*. 2019; 173: 118–124. <https://doi.org/10.1016/J.COMPOSITECH.2019.02.001>
 36. Ren M., Zhou Y., Wang Y., Zheng G., Dai K., Liu C., Shen Ch. Highly stretchable and durable strain sensor based on carbon nanotubes decorated thermoplastic polyurethane fibrous network with aligned wave-like structure. *Chemical Engineering Journal*. 2019; 360: 762–777. <https://doi.org/10.1016/J.CEJ.2018.12.025>
 37. del Bosque A., Sánchez-Romate X.F., Gómez A., Sánchez M., Ureña A. Highly stretchable strain sensors based on graphene nanoplatelet-doped ecoflex for biomedical purposes. *Sensors and Actuators A: Physical*. 2023; 353: 114249. <https://doi.org/10.1016/J.SNA.2023.114249>
 38. Wang Y., Hao J., Huang Z., Zheng G., Dai K., Liu C., Shen Ch. Flexible electrically resistive-type strain sensors based on reduced graphene oxide-decorated electrospun polymer fibrous mats for human motion monitoring. *Carbon*. 2018; 126: 360–371. <https://doi.org/10.1016/J.CARBON.2017.10.034>
 39. Bolton W. Control systems. *Control Systems*. 2002: 1–36. <https://doi.org/10.1016/B978-075065461-6/50001-5>
 40. Nechibvute A., Chawanda A., Luhanga P. Piezoelectric energy harvesting devices: an alternative energy source for wireless sensors. *Smart Materials Research*. 2012; 2012: 853481. <https://doi.org/10.1155/2012/853481>
 41. Tangsirinaruenart O., Stylios G. A novel textile stitch-based strain sensor for wearable end users. *Materials*. 2019; 12(9): 1469. <https://doi.org/10.3390/ma12091469>
 42. Gioberto G., Compton C., Dunne L.E. Machine-stitched E-textile stretch sensors. *Sensors & Transducers*. 2016; 202(7): 25–37. https://www.sensorsportal.com/HTML/DIGEST/july_2016/Vol_202/P_2837.pdf
 43. Ślowski S., Kciuk M., Klein W. Change in electrical resistance of SMA (NiTi) wires during cyclic stretching. *Sensors*. 2022; 22(9): 3584. <https://doi.org/10.3390/S22093584>
 44. Bailey P.B.S., Higham M. Application of strain-controlled fatigue testing methods to polymer matrix composites. *Procedia Structural Integrity*. 2016; 2: 128–35. <https://doi.org/10.1016/j.prostr.2016.06.017>
 45. Bhujangrao T., Froustey C., Iriondo E., Veiga F., Darnis P., Mata F.G. Review of intermediate strain rate testing devices. *Metals (Basel)*. 2020; 10(7): 894. <https://doi.org/10.3390/MET10070894>
 46. Koncar V. Smart textiles for in situ monitoring of composites. In: *Smart textiles for in situ monitoring of composites*; 2019. P. 397. <https://doi.org/10.1016/C2016-0-04506-0>
 47. Maričić A., Spasojević M., Kalezić-Glišović A., Ribić-Zelenović L., Djukić S., Mitrović N. The stress effect on electrical resistivity sensitivity of FeBSiC amorphous ribbon. *Sensors and Actuators A: Physical*. 2012; 174: 103–106. <https://doi.org/10.1016/J.SNA.2011.12.022>
 48. Ajovalasit A. The measurement of large strains using electrical resistance strain gages. *Experimental Techniques*. 2012; 36(3): 77–82. <https://doi.org/10.1111/j.1747-1567.2011.00761.x>
 49. Miodownik M., Oldfrey B., Jackson R., Smitham P. A deep learning approach to non-linearity in wearable stretch sensors. *Frontiers Robotics AI*. 2019; 6: 27. <https://doi.org/10.3389/frobt.2019.00027>
 50. Kumaresan Y., Mishra S., Ozioko O., Chirila R., Dahiya R. Ultra-high gauge factor strain sensor with wide-range stretchability. *Advanced Intelligent Systems*. 2022; 4(9): 2200043. <https://doi.org/10.1002/aisy.202200043>

51. Bae S.H., Lee Y., Sharma B.K., Lee H.J., Kim J.H., Ahn J.H. Graphene-based transparent strain sensor. *Carbon*. 2013; 51: 236–242. <https://doi.org/10.1016/J.CARBON.2012.08.048>
52. Kang D., Pikhitsa P.V., Choi Y.W., Lee C., Shin S.S., Piao L., Park B., Suh K.-Y., Kim T., Choi M. Ultrasensitive mechanical crack-based sensor inspired by the spider sensory system. *Nature*. 2014; 516: 222–226. <https://doi.org/10.1038/NATURE14002>
53. Boland C.S., Khan U., Backes C., O'Neill A., McCauley J., Duane S., Shanker R., Liu Y., Jurewicz I., Dalton A.B., Coleman J. Sensitive, high-strain, high-rate bodily motion sensors based on graphene-rubber composites. *ACS Nano*. 2014; 8(9): 8819–8830. <https://doi.org/10.1021/NN503454H>
54. Sensor terminology – NI. April 23, 2024. <https://www.ni.com/en-za/shop/data-acquisition/sensor-fundamentals/sensor-terminology.html#section-917347220> (accessed on 17.07.2023).
55. Jin L., Chortos A., Lian F., Pop E., Linder C., Bao Z., Cai W. Microstructural origin of resistance-strain hysteresis in carbon nanotube thin film conductors. *Proceedings of the National Academy of Sciences*. 2018; 115(9): 1986–1991. <https://doi.org/10.1073/pnas.1717217115>
56. Kim T.K., Kim J.K., Jeong O.C. Measurement of nonlinear mechanical properties of PDMS elastomer. *Microelectronic Engineering*. 2011; 88(8): 1982–1985. <https://doi.org/10.1016/j.mee.2010.12.108>
57. Liu C.X., Choi J.W. Analyzing resistance response of embedded PDMS and carbon nanotubes composite under tensile strain. *Microelectronic Engineering*. 2014; 117: 1–7. <https://doi.org/10.1016/j.mee.2013.11.013>
58. Borayek R., Foroughi F., Xin X., Mohamed A.M., Abdelrahman M.M., Zedan M., Zhang D., Ding J. Near-zero hysteresis ionic conductive elastomers with long-term stability for sensing applications. *ACS Applied Materials & Interfaces*. 2022; 14(9): 11727–11738. <https://doi.org/10.1021/acsami.1c24784>
59. Zhang Y., Zhu X., Liu Y., Liu L., Xu Q., Liu H., Wei W., Li Ch. Ultra-stretchable monofilament flexible sensor with low hysteresis and linearity based on MWCNTs/Ecoflex composite materials. *Macromolecular Materials and Engineering*. 2021; 306(8): 2100113. <https://doi.org/10.1002/MAME.202100113>
60. Achaiah N.C., Bhutta B.S., AK AK. *Fever in the intensive care patient*. StatPearls. August 17, 2023. <https://www.ncbi.nlm.nih.gov/books/NBK570583/> (accessed on 25.07.2023).
61. How is temperature affecting your strain measurement accuracy? NI. November 21, 2023. <https://www.ni.com/en-za/shop/data-acquisition/sensor-fundamentals/measuring-strain-with-strain-gages/how-is-temperature-affecting-your-strain-measurement-accuracy.html#section-638067164> (accessed on 25.07.2023).
62. Zhang T., Evans J.R.G., Rees D.W.A. The heating effect of electrical resistance strain gauges applied to low thermal conductivity materials. *Strain*. 1992; 28(3): 107–112. <https://doi.org/10.1111/J.1475-1305.1992.TB00803.X>
63. Zhao Y., Liu Y., Li Y., Hao Q. Development and application of resistance strain force sensors. *Sensors (Switzerland)*. 2020; 20(20): 5826. <https://doi.org/10.3390/S20205826>
64. Gaikar S.V., Deshmukh N.N. Effect of excitation voltage and lead wire resistance on strain measurement. In: *Proc. 2nd Inter. conf. for convergence in technology (I2CT)*. Mumbai, India; 2017. P. 747–752. <https://doi.org/10.1109/I2CT.2017.8226228>
65. Temperature coefficient of resistance – electrical information. <https://electrical-information.com/temperature-coefficient-of-resistance/> (accessed on 16.07.2023).
66. HKD peltier cooler 12V 60W – Communica. <https://www.comunica.co.za/products/hkd-peltier-cooler-12v-60w?variant=44293644517676> (accessed on 16.07.2023).
67. Tritt T.M. *Thermoelectric materials: principles, structure, properties, and applications*. Encyclopedia of materials: science and technology; 2002. P. 1–11. <https://doi.org/10.1016/B0-08-043152-6/01822-2>
68. Nankali M., Nouri N.M., Navidbakhsh M., Geran M.N., Amind-ehghan M.A., Montazeri Sh.A., Karimia M., Amjadi M. Highly stretchable and sensitive strain sensors based on carbon nanotube-elastomer nanocomposites: The effect of environmental factors on strain sensing performance. *Journal of Materials Chemistry C*. 2020; (18): 6185–6195. <https://doi.org/10.1039/d0tc00373e>
69. Górski M., Krzywoń R., Kekez S. Air humidity-induced error in measuring resistance of a carbon fibre strain sensor. *Archives of Civil Engineering*. 2020; 66(3): 157–171. <https://doi.org/10.24425/ace.2020.134390>
70. Wangyanfeng, Zhaoxiaohua, Zhaoyi, Bianyadong. Effects of moisture on mechanical and piezoresistive properties of cement composites containing carbon fiber during long age. In: *5th Inter. conf. on advances in energy, environment and chemical science (AECS 2021)*. E3S Web of Conferences. 2021; 245: 03061. <https://doi.org/10.1051/e3sconf/202124503061>
71. Buasiri T., Habermehl-Cwirzen K., Krzeminski L., Cwirzen A. Novel humidity sensors based on nanomodified Portland cement. *Scientific Reports*. 2021; 11: 8189. <https://doi.org/10.1038/s41598-021-87563-7>
72. Demircilioğlu E., Teomete E., Schlangen E., Baeza F.J. Temperature and moisture effects on electrical resistance and strain sensitivity of smart concrete. *Construction and Building Materials*. 2019; 224: 420–427. <https://doi.org/10.1016/j.conbuildmat.2019.07.091>
73. Górski M., Krzywoń R., Kekez S. The effect of humidity on the electrical resistance of smart sensor based on carbon fibers. *Preprints*. 2019; 2019020069. <https://doi.org/10.20944/preprints201902.0069.v1>
74. Ding S., Dong S., Ashour A., Han B. Development of sensing concrete: Principles, properties and its applications. *Journal of Applied Physics*. 2019; 126: 241101. <https://doi.org/10.1063/1.5128242/156653>
75. Yamada T., Hayamizu Y., Yamamoto Y., Yomogida Y., Izadi-Najafabadi A., Futaba D.N., Hata K. A stretchable carbon nanotube strain sensor for human-motion detection. *Nature Nanotechnology*. 2011; 6: 296–301. <https://doi.org/10.1038/NNANO.2011.36>
76. Hwang B.U., Lee J.H., Trung T.Q., Roh E., Kim D.II, Kim S.W., Lee N.E. Transparent stretchable self-powered patchable sensor platform with ultrasensitive recognition of human activities. *ACS Nano*. 2015; 9(9): 8801–8810. <https://doi.org/10.1021/acs.nano.5b01835>
77. Amjadi M., Yoon Y.J., Park I. Ultra-stretchable and skin-mountable strain sensors using carbon nanotubes-Ecoflex nanocomposites. *Nanotechnology*. 2015; 26(37): 375501. <https://doi.org/10.1088/0957-4484/26/37/375501>
78. Terrile S., Miguelañez J., Barrientos A. A soft haptic glove actuated with shape memory alloy and flexible stretch sensors. *Sensors*. 2021; 21(16): 5278. <https://doi.org/10.3390/s21165278>

79. Pacelli M., Loriga G., Taccini N., Paradiso R. Sensing fabrics for monitoring physiological and biomechanical variables: E-textile solutions. In: *Proc. of the 3rd IEEE-EMBS Inter. summer school and symposium on medical devices and biosensors, ISSS-MDBS*. Cambridge, MA, USA; 2006. P. 1–4. <https://doi.org/10.1109/ISSS-MDBS.2006.360082>
80. Scilingo E.P., Lorussi F., Mazzoldi A., De Rossi D. Strain-sensing fabrics for wearable kinaesthetic-like systems. *IEEE Sensors Journal*. 2003; 3(4): 460–467. <https://doi.org/10.1109/JSEN.2003.815771>
81. Paradiso R., Loriga G., Taccini N. A wearable health care system based on knitted integrated sensors. *IEEE Transactions on Information Technology in Biomedicine*. 2005; 9(3): 337–344. <https://doi.org/10.1109/TITB.2005.854512>
82. Textile sensor breathing belt. Plusea. Flickr. <https://www.flickr.com/photos/plusea/49781645282> (accessed on 3 October 2022).
83. Breathing belt. <https://www.kobakant.at/DIY/?p=8171> (accessed on 03.10.2022).
84. A breathing sensor / respiration belt by @kobakant «Adafruit Industries – Makers, hackers, artists, designers and engineers! April 28, 2020. <https://blog.adafruit.com/2020/04/28/a-breathing-sensor-belt-by-kobakant/> (accessed on 03.10.2022).
85. Mukhopadhyay B., Sharma O., Kar S. IoT based wearable knitted fabric respiratory monitoring system. In: *Proc. Conf. IEEE SENSORS*. New Delhi, India; 2018. P. 1–4. <https://doi.org/10.1109/ICSENS.2018.8589540>
86. Hempel M., Nezich D., Kong J., Hofmann M. A novel class of strain gauges based on layered percolative films of 2D materials. *Nano Letters*. 2012; 12(11): 5714–5718. <https://doi.org/10.1021/nl302959a>
87. Xiao X., Yuan L., Zhong J., Ding T., Liu Y., Cai Z., Rong Y., Han H., Zhou J., Wang Zh.L. High-strain sensors based on ZnO nanowire/polystyrene hybridized flexible films. *Advances in Materials*. 2011; 23(45): 5440–5444. <https://doi.org/10.1002/adma.201103406>
88. Park J.J., Hyun W.J., Mun S.C., Park Y.T., Park O.O. Highly stretchable and wearable graphene strain sensors with controllable sensitivity for human motion monitoring. *ACS Applied Materials & Interfaces*. 2015; 7(11): 6317–6324. <https://doi.org/10.1021/ACSA-MI.5B00695>
89. Wang Y., Wang L., Yang T., Li X., Zang X., Zhu M., Wang K., Wu A., Zhu H. Wearable and highly sensitive graphene strain sensors for human motion monitoring. *Advanced Functional Materials*. 2014; 24(29): 4666–4670. <https://doi.org/10.1002/ADFM.201400379>
90. De Vivo B., Lamberti P., Spinelli G., Tucci V., Vertuccio L., Vittoria V. Simulation and experimental characterization of polymer/carbon nanotubes composites for strain sensor applications. *Journal of Applied Physics*. 2014; 116: 54307. <https://doi.org/10.1063/1.4892098>
91. Hu A.N., Fukunaga H., Atobe S., Liu Y., Li J. Piezoresistive strain sensors made from carbon nanotubes based polymer nanocomposites. *Sensors*. 2011; 11(11): 10691–10723. <https://doi.org/10.3390/S111110691>
92. Amjadi M., Pichitpajongkit A., Lee S., Ryu S., Park I. Highly stretchable and sensitive strain sensor based on silver nanowire-elastomer nanocomposite. *ACS Nano*. 2014; 8(5): 5154–5163. <https://doi.org/10.1021/nn501204t>
93. Wu S., Zhang J., Ladani R.B., Ravindran A.R., Mouritz A.P., Kinloch A.J., Wang Ch.H. Novel electrically conductive porous PDMS/carbon nanofiber composites for deformable strain sensors and conductors. *ACS Applied Materials & Interfaces*. 2017; 9(16): 14207–14215. <https://doi.org/10.1021/acsami.7b00847>
94. Kong J.-H., Jang N.-S., Kim S.-H., Kim J.-M. Simple and rapid micropatterning of conductive carbon composites and its application to elastic strain sensors. *Carbon*. 2014; 77: 199–207. <https://doi.org/10.1016/j.carbon.2014.05.022>
95. Kurian A.S., Souri H., Mohan V.B., Bhattacharyya D. Highly stretchable strain sensors based on polypyrrole-silicone rubber composites for human motion detection. *Sensors and Actuators A: Physical*. 2020; 312: 112131. <https://doi.org/10.1016/J.SNA.2020.112131>
96. Muth J.T., Vogt D.M., Truby R.L., Mengüç Y., Kolesky D.B., Wood R.J., Lewis J.A. Embedded 3D printing of strain sensors within highly stretchable elastomers. *Advanced Materials*. 2014; 26(36): 6307–6312. <https://doi.org/10.1002/adma.201400334>
97. Lee S., Koo J., Kang S.-K., Park G., Lee Y.J., Chen Y.-Y., Lim S.A., Lee K.-M., Rogers J.A. Metal microparticle – Polymer composites as printable, bio/ecoresorbable conductive inks. *Materials Today*. 2018; 21(3): 207–215. <https://doi.org/10.1016/J.MAT-TOD.2017.12.005>
98. Siwek W.R., Sapoff M., Goldberg A., Johnson H.C. A precision temperature standard based on the exactness of fit of thermistor resistance-temperature data using third degree polynomials. N.Y.: American Institute of Physics; 1992.
99. Sapoff M., Siwek W.R., Johnson H.C., Slepian J., Weber S. The exactness of fit of resistance-temperature data of thermistors with third-degree polynomials. In: Schooley J.E. (ed.). *Temperature, its measurement and control in science and industry*. N.Y.: American Institute of Physics; 1982. Vol. 5. P. 875–888.