



HAL
open science

Stretchable piezoresistive textile yarn strain transducer for low deformation detection

Hankai Wu, Fabrice Seguin, Vladan Koncar, Cédric Cochrane, Laurent Dupont, Cyril Lahuec, Alexandre Khaldi

► **To cite this version:**

Hankai Wu, Fabrice Seguin, Vladan Koncar, Cédric Cochrane, Laurent Dupont, et al.. Stretchable piezoresistive textile yarn strain transducer for low deformation detection. *Sensors and Actuators A: Physical*, 2023, 363, <10.1016/j.sna.2023.114755>. <hal-04253877>

HAL Id: hal-04253877

<https://imt-atlantique.hal.science/hal-04253877v1>

Submitted on 23 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Copyright - All rights reserved

Stretchable piezoresistive textile yarn strain transducer for low deformation detection

Hankai Wu ^{a,b}, Fabrice Seguin ^{a,b}, Vladan Koncar ^c, Cédric Cochrane ^c, Laurent Dupont ^a, Cyril Lahuec ^{a,b} and Alexandre Khaldi ^{a*}

^a Optics department, IMT Atlantique, Brest 29238, France

^b Lab-Sticc, UMR6285, IMT Atlantique, Brest 29238, France

^c Univ. Lille, ENSAIT, ULR 2461 - GEMTEX - Génie et Matériaux Textiles, F-59000 Lille, France

Abstract

Stretchable piezoresistive transducers for strain sensing have been widely developed because of their remarkable sensitivity, elasticity, and cyclability. In this work, commercial elastane yarn (Lycra[®] 1880 dtex) is functionalized by a conductive polymer poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) with a dip-coating method. Poly(ethylene glycol) diacrylate (PEGDA) is used as a beneficial additive to improve the affinity between the elastic substrate and the conductive layer. Indicating a small modification of the yarn's mechanical properties, Young's modulus of 3.5 MPa is observed for the transducer. An initial resistance of 3487 Ω is measured for a length of 50 mm. After a training stage involving 100 stretching/releasing cycles to stabilize the electromechanical properties related to morphological structure, the transducer exhibits an average gauge factor of 25 for the interest strain range (0 – 5%). Furthermore, the cyclability of the yarn is demonstrated by 10,000 deformation cycles with only a slight modification of the relative resistance variation.

Keywords: piezoresistive transducer, PEDOT:PSS, elastane, flexible fiber, dip-coating

1. Introduction

Over the last decades, thanks to the technologies of conjugated polymeric materials, stretchable textile transducers for strain sensing have been widely developed [1]. This material type can transduce a mechanical deformation into a measurable electrical signal, and can be used in various promising applications, such as human motion monitoring [2], healthcare [3], soft robotics [4], internet of things [5], and flow sensing [6]. One of the most commonly used methods to achieve piezoresistive properties is the functionalization of textile yarn to make it conductive, primarily due to the wide commercial availability of different yarns. Additionally, they can be easily integrated into engineering systems [7] and transformed into textile fabrics using well-established textile shaping technologies like weaving, knitting, and braiding [8].

Various methods of functionalization of stretchable polymeric materials exist to elaborate piezoresistive textile fibers [9–11]. Percolation of conductive particles onto yarn fabrication is a possible way of functionalization. For example, Wang et al. described a dip coating method by using single-wall carbon nanotubes (SWCNT) onto a polyurethane (PU)/cotton yarn [12]. Their transducer shows a sensing range of up to 300% and a gauge factor (GF) of around 0.65. However, reaching the percolation of such conductive particles is very difficult, presenting a barrier to upscaling this type of process.

Coating conductive materials onto a flexible substrate is one of the most used methods because it is possible to avoid affecting the substrates' mechanical properties [13]. Piezoresistive transducers can be achieved using conjugated polymers, such as polypyrrole [14], polyaniline (PANI) [15], and poly(3,4-ethylenedioxythiophene) (PEDOT) [16,17]. Fan et al. reached a GF of

about 3 at 400% of strain with a PANI coated PU fiber strain sensor by applying an in-situ polymerization method [15].

Poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) is a commercial conjugated polymer with PSS as a charge balancing counterion of PEDOT to obtain a stable aqueous dispersion. Thanks to its remarkable electrical, optical, and mechanical properties, this material is widely used for different purposes and various ways of processing are reported, such as ink-printing, spray coating, spin coating, and dip coating [18–20]. However, usually, the elastic substrates are hydrophobic materials, then PEDOT:PSS has low adhesion forces towards these substrates, and additives such as polyethylene oxide (PEO) can be used to enhance the affinity between the conducting polymer and the hydrophobic substrates [21].

Many academic researches focus on fabricating transducers with stretchability as high as possible [22], but to our knowledge, few yarns have been produced achieving high sensitivity under low forces/low strain. For low forces/low strain detection it is necessary to use elastomeric materials. However, it is difficult to obtain a high piezoresistive effect for low forces/deformation since the conductive layer does not undergo many physical changes on elastomeric material, *i.e.* structuration of conducting layer or geometrical changes inducing variation of electrical resistance. We summarize in Table 1 the properties of a few yarn sensors developed for low strain detection [23-30].

Table 1: review of few yarn transducers developed for low strain detection (N/A for not announced)

Materials	Fabrication method	Initial electrical resistance	Sensing range	Gauge factor	Cyclic stability
PU/carbon black@cellulose nanocrystals/natural rubber [23]	Conductive polymer composite/layer by layer	1.9 M Ω /cm for 80 layers	4%	38.9 at 1% strain	10 000 cycles at 1% strain
Silk/Graphite flakes [24]	Rod coating	N/A	15%	14.5 at 15% strain	3000 cycles at 10% strain
PU/ZnO nanowires [25]	Hydrothermal reaction	N/A	1.8% to 150%	15.2 at <10% strain 4.1 at 10-150% strain	10 000 cycles between 8.7% and 23.2% strain
PU/silver nanowires/graphene [26]	Coprecipitation, reduction, vacuum filtration and casting	N/A	1%	20 at <0.3%, 1000 between 0.3% and 0.5%, 4000 between 0.8% and 1%	1000 cycles at 0.6% strain
Polycarbonate/multiwall carbon nanotube [27]	Melt-spinning composite fiber	Resistivity ~ 50 M Ω .cm	~6%	~16 at 2% strain (3.5wt% MWCNT, draw down ratio 8.08)	N/A

Silicone/PEDOT:PSS [28]	Direct deposition onto a plasma-treated polyethylene film with protective silicone layer	$10^{3.2} \Omega$ for sample with 15wt% of PEDOT:PSS at length of 100 mm	<10%	6.9	-
PEDOT/sulfated nanocellulose [29]	In-situ polymerization	-	1.5%	3.2	9 cycles
AgNW/PEDOT:PSS/PU [30]	Spin-coating	-	6%	11.14	50 cycles

Overall, from the performance of the transducers presented in Table 1, it can be concluded that it is very difficult to combine the properties of high conductivity, high gauge factors, high deformation range, and of significant cyclable response in the low deformation range with process of fabrication which can be industrialized.

This is why we aim to develop a transducer based on a commercial yarn and a commercial conductive solution with simple dipping methods of functionalization. We fabricated a stretchable piezoresistive transducer based on Lycra® 1880 dtex (dtex = g/10 000m) as elastic substrate and functionalized with PEDOT:PSS and present its electromechanical properties. We show that the proposed functionalization protocol has a low impact on the mechanical properties and that the transducer keeps a highly elastic nature with a young modulus E in the order of MPa. The use of Lycra® fibers as substrate is one of the main innovations shown in our article comparing to the papers cited in Table 1. However, this is also the main problem because Lycra® is much more elastic than the coated layer leading to mechanical mismatch.

Indeed, when a structural material is coated with a conductive material, there is often a mechanical mismatch (different mechanical properties such as young modulus) between the two materials. This mechanical mismatch causes structural changes during the first cycles of deformation impacting the stability of the electrical resistance of the transducer. That is why, we propose to impose a training stage at a higher strain range, 20%, than the strain range of interest, 5%, to stabilize, and improve the electromechanical response of the transducer. Training creates cracks in the conductive layer so that the transducer exhibits a stable and improved sensitivity in the 0-5% strain range. This training stage is another innovation in our approach supposed to develop highly stretchable sensory yarns. Moreover, the transducer is stretched in dynamic and static modes with attention to the cyclability of the transducers.

Comparing to other sensory yarns mentioned in Table 1, our yarns, before undergoing the training process, exhibit a broad measurement range (between 0 and 70%) with macroscopic linear behavior and gauge factor approximately equal to 1 on the entire range of measurements.

2. Materials and methods

2.1. Materials

The Lycra® 1880 dtex containing 112-micrometer multi-threads is graciously provided by Filix company (France). PEDOT:PSS aqueous commercial ink (Clevios® P, solid content of 1.3wt%) was ordered from Heraeus™ (Germany). Poly(ethylene glycol) diacrylate (PEGDA, $M_n=700$), azobisisobutyronitrile (AIBN), methyl methacrylate (MMA), and dichloromethane (DCM) are purchased from Merck and used as received.

2.2. Transducer functionalization protocol

The functionalization protocol is schematized in Figure 1(a).

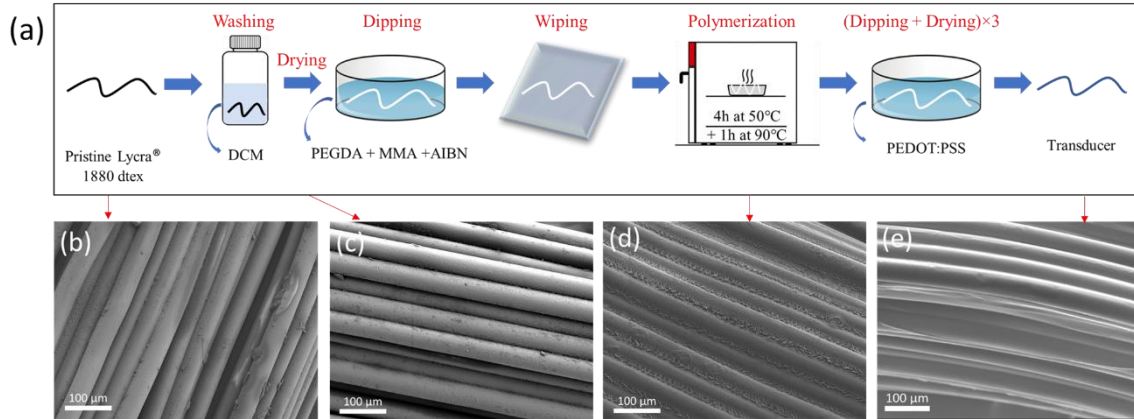


Figure 1: Functionalization protocol of the Lycra® 1880 dtex, SEM images of the yarn at different fabrication steps: (b) pristine Lycra® yarn; (c) DCM washed yarn; (d) yarn after PEGDA polymerization and (e) PEDOT:PSS covered yarn.

The first step of the protocol consists in washing the pristine Lycra® 1880 dtex, Figure 1 (b), by dipping it in DCM for 72 h and then drying it in an oven at 40°C for 4 h. During the fabrication of Lycra®, silicone is added to improve the mechanical properties of elastane. This washing step allows removing some of the silicone localized at the surface of the fiber to enable the yarn functionalization. Washing induces a weight loss of 6%, ($\Delta m/m_0$, where Δm is the difference of mass before and after washing and m_0 is the mass before washing). Figure 1(c) illustrates the surface morphology of the fiber after this washing step. Circular evaporation marks of DCM are observed after this washing step (Figure S1 in supplementary information).

An attempt was made to dip-coat PEDOT:PSS onto the washed Lycra® 1880 dtex yarn (without PEGDA). The yarn is soaked in the dispersion of PEDOT/PSS for 1 min and dried in a desiccator for 15 min at 60°C under a vacuum of -60 cmHg. With a repetition of 7 times of this process, the observed resistance is 10 M Ω for a length of 50 mm.

The PEGDA precursor solution includes 88.5 wt% of PEGDA, 8.5 wt% of MMA as the reactive solvent, and 3 wt% of AIBN as the thermal initiator. The mixture is stirred until the total dissolution of AIBN. Thereafter, the washed textile is soaked in the PEGDA precursor solution for 24 h and wiped with absorbent paper to eliminate the precursor in excess at the surface and between the filaments. The in-situ polymerization of PEGDA is achieved with a heat treatment in an oven for 4 h at 50°C, followed by a post-curing step for 1 h at 90°C. Yarn containing polymerized PEGDA is shown in Figure 1(d). On Figure S2, it is shown that the polymerization of PEGDA takes place at the surface of elastane threads and between the filaments. Even if the yarn is wiped with absorbent paper after soaking, the capillarity effect traps the precursor solution between filaments.

Finally, to deposit the conductive layer, the textile is soaked 3 times in the PEDOT:PSS dispersion for 1 min and then dried in a desiccator for 15 min at 60°C under a vacuum of -60 cmHg. The yarn out of fabrication is uniformly covered by PEDOT:PSS to yield the transducer, Figure 1(e). The conductive yarn installed on the material testing machine is shown in Figure 2(a). The resulting resistance observed after functionalization is $R_0 = 3487 \pm 2032 \Omega$ for a sample with a length of 50 mm, the uncertainty corresponds to the resistance measurements of samples from 5

batches of fabrication. For the conductive yarn used in the training study, the R_0 value is $3512 \pm 12 \Omega$, the uncertainty corresponding to the resistance measurement of 3 samples from the same batch of fabrication. Since it was not possible to achieve a conductive material with the same PEDOT/PSS functionalization onto washed Lycra® yarn, it can be concluded from this resistance measurements that poly(ethylene glycol) diacrylate (PEGDA) functionalization of washed Lycra® yarn improves the affinity between the elastic substrate and the conductive PEDOT:PSS layer.

2.3. Characterization methods

During the fabrication of the transducer, the Young's Modulus (E) of yarns at different steps is contrasted to analyze the mechanical properties modification.

The yarn's mechanical properties are characterized by means of a material testing machine (LS1 from Lloyd, USA) allowing uniaxial stretching/releasing deformation. The material testing machine is equipped with a force sensor with a capacity of 5 N (XLC Series Load Cell from Lloyd, USA). The fabricated transducer is fixed using 2 couples of clamps on both sides of the LS1. For each couple of clamps, one part is stuck on a piece of double-sided tape to avoid slipping the yarn, and another is clamped with a copper strip to establish a robust electrical connection. The LS1 is preset so that the yarn to be tested has an initial length of 50 mm and an applied pre-charge of 0.01 N. Measuring the straight stress (σ) according to strain (ε) allows computing the yarn's E as the slope of $\sigma = f(\varepsilon)$ at the origin (1).

$$\sigma = E \times \varepsilon = E \times \frac{l_t - l_0}{l_0} \quad (1)$$

where l_t is the length at time t and l_0 is the initial length before deformation.

The electrical resistance of the yarns as they undergo n cycles of mechanical deformations is measured using a source meter unit (KEITHLEY SMU 2450, USA). Then, the electromechanical properties are represented by the GF calculated as the ratio of electrical resistance variation for a strain range over the initial resistance value for each cycle (2).

$$GF = \frac{\frac{\Delta R_n}{R_{0,n}}}{\Delta \varepsilon} = \frac{(R_{t,n} - R_{0,n})}{R_{0,n} \Delta \varepsilon} \quad (2)$$

where $R_{0,n}$ is the releasing resistance at the beginning of cycle n , $R_{t,n}$ is the resistance at the end of the stretching step for this cycle, and $\Delta \varepsilon$ is the strain range of the experiment (5% in our case). The gauge factor depends on the strain range applied to the transducer.

Fifty cycles are selected from the total number of electromechanical characterization cycles to compute an average GF . The cycles are selected as follows; the time taken to run all the cycles is divided by 50 to form a sample time slot. Then, the cycle at the end of each time slot is selected as a sample cycle to compute the average GF . So that samples are taken evenly over the test.

The morphology of the fibers at different steps of functionalization is studied with scanning electron microscopy (SEM, SH-4000 from Hirox, Europe).

3. Results and discussions

3.1. Mechanical properties and morphological studies

The stress-strain experiment results of the yarn at different steps of the transducer fabrication for strains ranging from 0 up to 200% are shown in Figure 2(b). The corresponding

computed E values are reported in Table 2 (values averaged from 5 experiments of 5 samples, the uncertainty representing the extreme values).

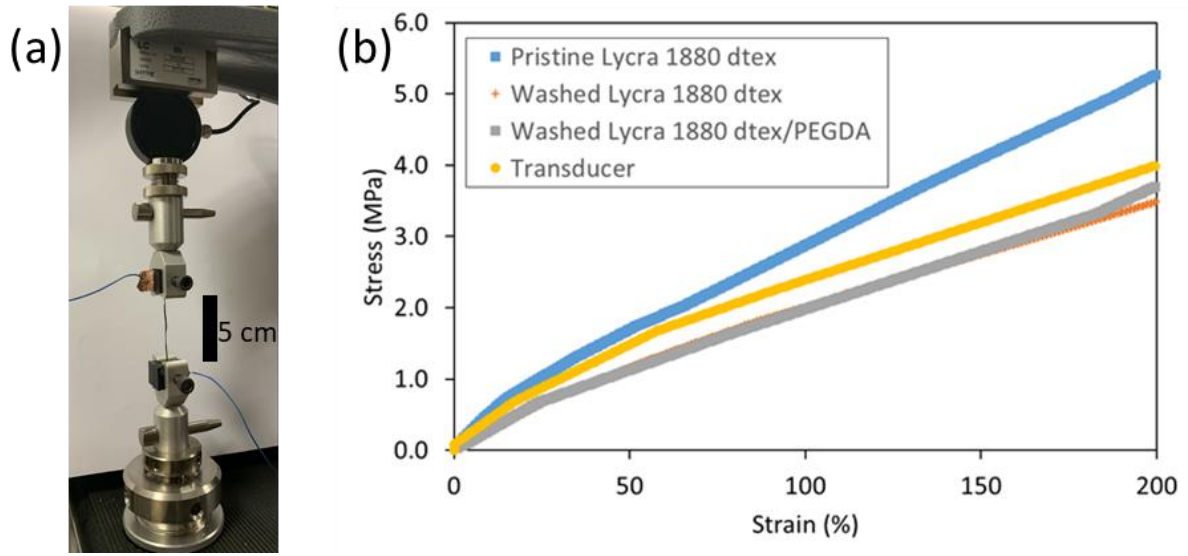


Figure 2: (a) Conductive yarn installed on the material testing machine. (b) Measured yarn stress according to strain at different fabrication steps.

Table 2: Young modulus of the yarn at different fabrication steps

Transducer fabrication step	E (MPa)
Pristine Lycra® 1880 dtex	4.5 ± 0.7
Washed Lycra® 1880 dtex	2.6 ± 0.2
Washed Lycra® 1880 dtex / PEGDA	2.8 ± 0.1
Transducer	3.5 ± 0.3

Removal of part of the silicone by washing in DCM is supported by a measured 6% weight loss and, moreover, by a decrease in E , $E = 4.5$ MPa before washing and $E = 2.6$ MPa after. Figure 2(b) shows similar mechanical properties between the washed yarns with or without polymerized PEGDA as the two curves overlap each other, and the E are slightly different (2.8 and 2.6 MPa, respectively). The functionalized yarn is more rigid than the yarn in the previous steps, an effect of the addition of the PEDOT:PSS layer who has a young modulus of 1.5 GPa [31,32]. According to these experiments, it can be concluded that, even if the mechanical properties change from 2.6 to 3.5 MPa from the yarn washed states to the final transducer during the fabrication process, the material keeps the native elasticity of the pristine elastane yarns and has a lower Young modulus of pristine Lycra yarn. This is obtained, however, at the expense of the mechanical stability of the multi-thread yarn due to silicone removal but which enables the deposit of a PEDOT:PSS layer that brings electrical conductivity to the yarn. The next step is to check if the transducer is able to deform under low forces with piezoresistive capacity for different use cases.

3.2. Electromechanical studies

Simultaneous analysis of the mechanical and electrical properties must be realized to understand the behavior of the fabricated transducer.

The transducer resistance variation was tested out of synthesis with linear strain increase at a constant stretching speed of 100 mm/min, and also characterized by cyclic test for the strain of 5% with 100 cycles. Results are presented in Figure 3.

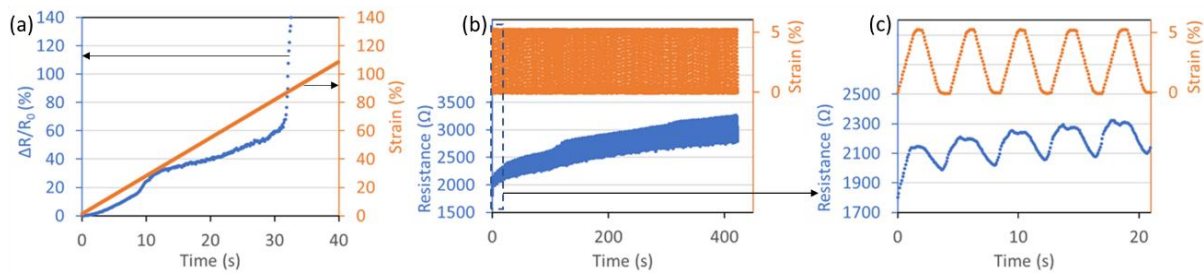


Figure 3: (a) Stretching the transducer up to 110%, conductive path rupture is observed at a strain of 85%; (b) cyclic test of transducer out of synthesis with 100 cycles at 5% of strain and (c) the first 5 cycles.

As shown in Figure 3(a), for this transducer, the electrical resistance increases with extension. There are two linear variations of resistance in two deformation ranges (0-20% and 40-85%) and a transition is occurring with higher resistance variation between 20 and 40% strain. We suppose that the variation of relative resistance over the range of deformation is due to several reasons: the formation of cracks on the multi-thread fibers, the thinning of conductive layer caused by Poisson's effect [33], rearrangement of multi-threads fiber geometry (sliding of individual threads – a decrease of distance between external functionalized threads). When the strain reaches 85%, a rupture of the conductive path is observed, represented by the steep increase in the resistance value. The discontinuity of the conductive layer occurs at this high strain, correlated with bleaching of the yarn corresponds to delamination of the PEDOT:PSS layer. This delamination is due to the difference of the E between the Lycra® 1880 dtex/PEGDA and the PEDOT:PSS layer (respectively 2.8 MPa and 1.5 GPa [32]), there is a mechanical mismatch between these two materials corresponding to the different susceptibility of the materials to deform. This effect causes delamination at 85% strain deformation of the conductive layer. The Lycra® 1880 dtex yarn exhibits complex mechanical behaviors under stretching since it has a multi-thread configuration.

Thereafter, the transducer out of synthesis is characterized over an arbitrarily fixed strain range between 0 and 5%. From Figures 3(b) and 3(c) we can observe that both stretching and releasing resistance increase during the test. The resistance value raises from 1800 Ω initially to 2802 Ω at the end for 100 cycles of deformation. Also, the amplitude of resistance variation deviates progressively from $\Delta R_1 = 343 \Omega$ for the first cycle to $\Delta R_{100} = 464 \Omega$ for the last one, represented increases of 15% and 19% respectively. Despite this deviation, the GF calculated with the last cycle is 3. However, for a transducer, it is ideal to carry a constant variation.

So that to stabilize the electromechanical properties of such yarns, a training stage that consists of cyclically deforming it with a higher strain magnitude is proposed. This training stage may enable fixing the electromechanical properties of the transducer. Because there is an interest in sensing very low forces in the range of 0-5% deformation, we chose to train the transducer with 100 cycles of stretching/releasing with a 20% strain at a velocity of 100 mm/min. Figure 4 presents the electrical resistance value variations versus time during the training stage.

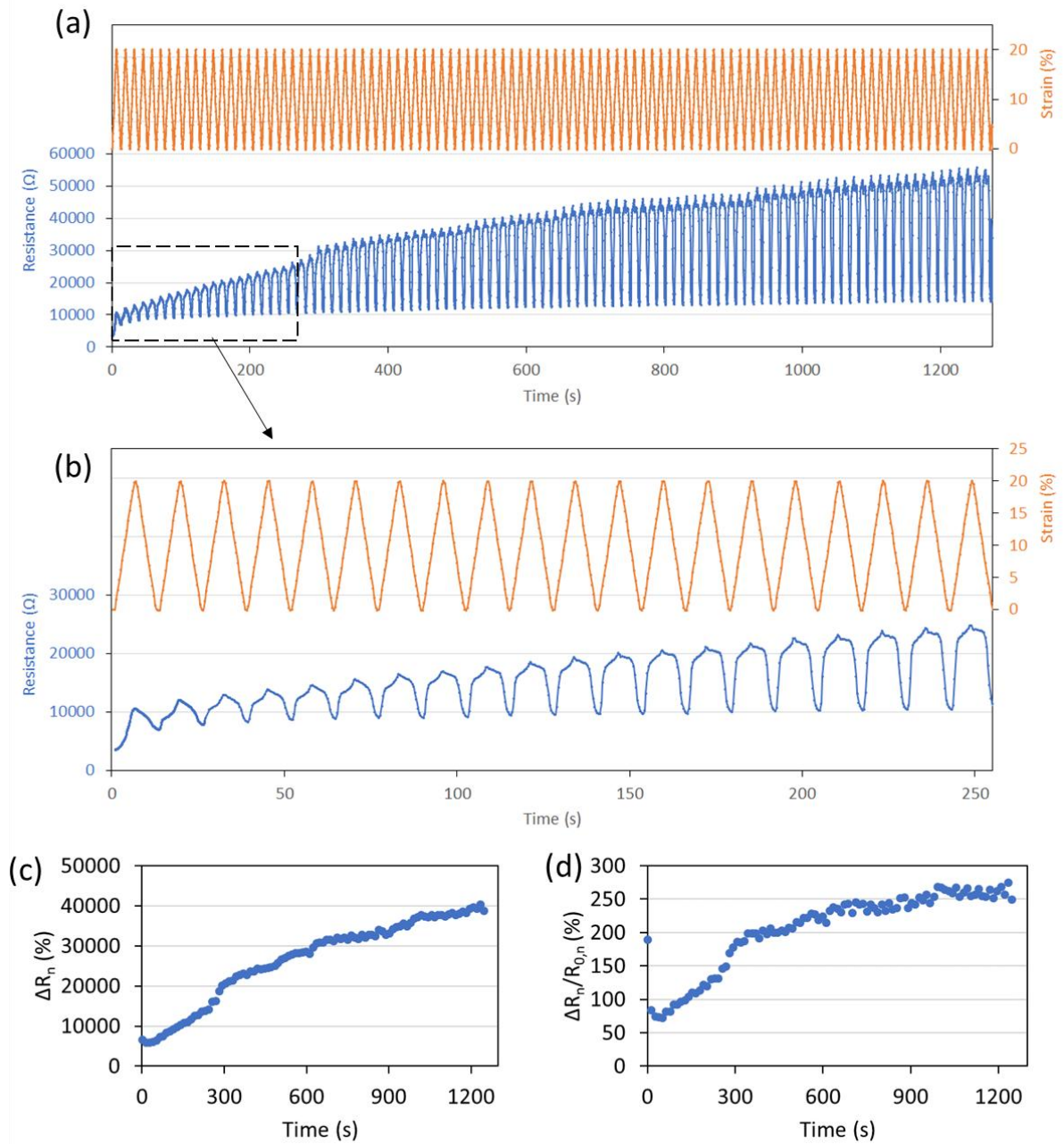


Figure 4: Training stage (a) corresponding to 100 stretching/releasing cycles and (b) the first 20 cycles. (c) Absolute resistance variation between released and stretched state of the yarn for each cycle and (d) relative resistance variation towards releasing resistance value for each cycle.

The initial electrical resistance $R_{0,1}$ of the transducer after fabrication is 3519 Ω with an initial length of 50 mm under a pre-charge of 0.01 N. During the training stage, the resistance of the transducer increases in the stretching step and decreases during the releasing step. An absolute or relative resistance variations can be deduced from electrical resistance in the stretching and releasing state for each cycle, ΔR_n and $\Delta R_n/R_{0,n}$ respectively in Figures 4 (c) and 4 (d). In the first five cycles of the training stage, the increase of releasing resistance, correlated with high irreversible morphological changes occurring in the coated conductive layer onto the elastomeric substrate, is predominant on $\Delta R_n/R_{0,n}$. It results in a decrease of the relative resistance variation from 189% to 72%. From the 5th to the 100th cycle of the training stage, the continuous

increase of the stretching resistance become predominant and results in the continuous increase of relative resistance variation from $\Delta R_5/R_{0,5} = 72\%$ (with $\Delta R_5 = 6402 \Omega$) to $\Delta R_{100}/R_{0,100} = 263\%$ (with $\Delta R_{100} = 38570 \Omega$), demonstrating quantitatively the enhancement of the resistance variation triggered by repeated identical mechanical deformation. The increase of the stretching resistance to 53226Ω in the 100th cycle, indicates that breakdown in the conductive layer arises by stimulating the textile yarn at 20% strain, without losing the electrical conductivity allowing the solicitation of such yarn in a lower degree of elongation.

The increase of electrical resistance in the stretched state for the same repeated 20 % strain mechanical stimulus is due to the increase of cracked wrinkle quantity at the surface of the yarn, Figure 5(d). Indeed, a cracked wrinkle generates a local electrical separation in the stretched state due to the isolation spacing appearing at the crack's location, thus slightly increasing the electrical resistance of the yarn. The overall yarn resistivity increases significantly due to the large quantity of cracked wrinkles generated during the training process... When the transducer returns to its released state, the cracked wrinkles reconnect physically, thus decreasing back the electrical resistance of the yarn. This explains why the progressive appearance of cracked wrinkles predominantly affects the stretching resistance in comparison to the releasing resistance from the fifth cycle of the training stage.

To understand the structure–properties relationships of the transducers, the morphological properties of the transducer before and after training have been studied by SEM and are shown in Figure 5.

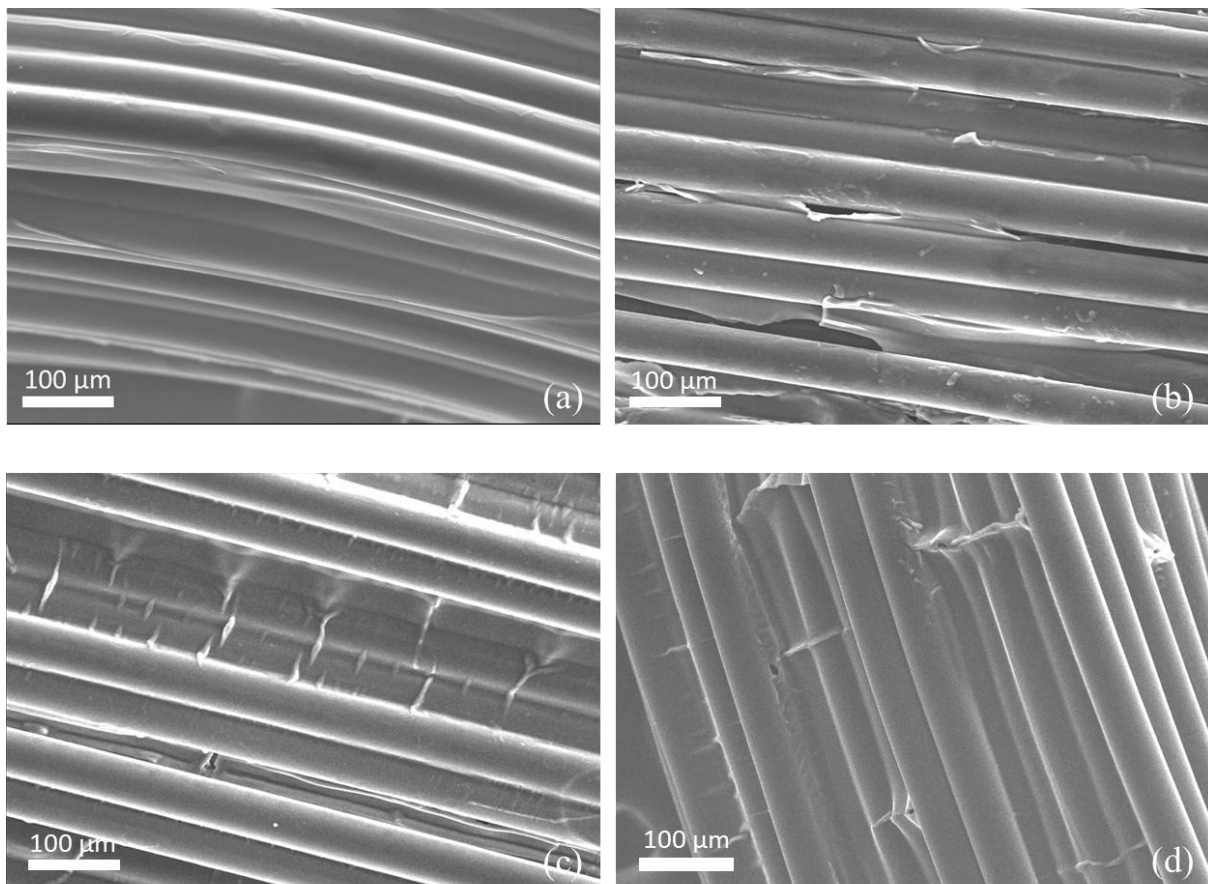


Figure 5: SEM image of transducer (a) before training; (b) after training with cracks parallel to the deformation direction; (c) and (d) after training with cracked wrinkles perpendicular to the deformation direction of the conductive layer.

Before the training stage, the conductive layer of PEDOT:PSS is uniformly coated at the surface of the yarn, Figure 5(a). After the 100 training cycles, two different types of cracked wrinkles appear simultaneously and randomly at different locations along the yarn: parallel to the direction of stretching due to the separation of the threads in the multi-thread yarn, Figure 5(b), and perpendicular to the deformation direction, Figure 5(c) and 5(d). Following the stretching of substrate yarn, the conductive layer elongates as well. However, as this conductive layer (PEGDA and PEDOT:PSS) is less elastic than the substrate, the extension involves its higher plastic deformation than Lycra. This phenomenon should generate wrinkling perpendicular to the deformation direction. Indeed, the substrate is released to its original length, cracked wrinkles (we choose to call it cracks) in the conductive layer are observed, Figure 5(d). The fiber behavior allows a reduction of the conductive pathways at the same cracks location from one stretch to another, providing memory and resulting in a high piezoresistive effect of the transducer. These cracks lead to a stable and appreciable variation of resistance according to mechanical deformation [34]. 20% of strain for the training stage is the minimum percentage (17% strain is not enough, Figure S4) to stabilize and simultaneously enhance the performance of the transducer. A continuous increase of crack quantity during training correlates to the augmentation of releasing resistance shown in Figure 4(a), and this without irreversible and total breakage.

Directly after training, and for the strain range of interest, *i.e.* from 0 to 5%, the cyclic stabilization of the transducer is analyzed with 10,000 stretching/releasing cycles at a speed of 100 mm/min, to study the aging of the material in dynamic condition of use, as shown in Figure 6.

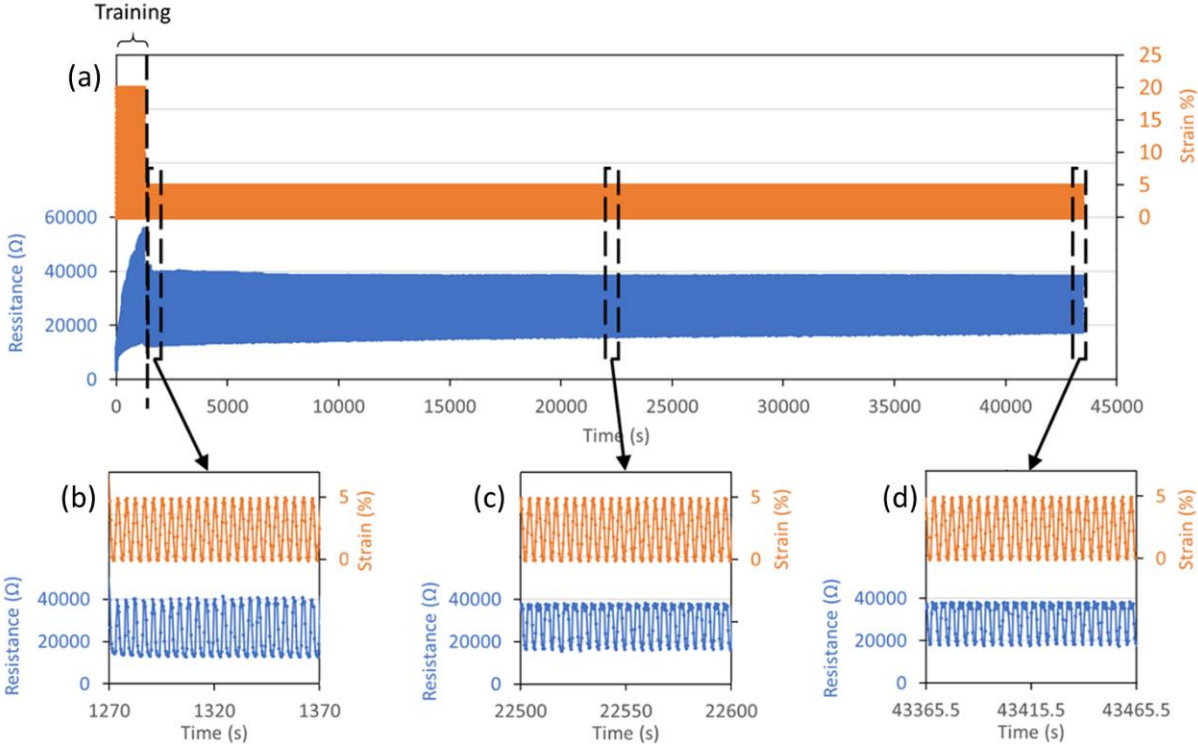


Figure 6: (a) Transducer electromechanical properties testing results, the 100 training cycles at 20% strain corresponds to the first 1270 seconds., followed by 10000 cycles at strain up to 5%; (b) the 23 cycles of the beginning of characterization; (c) the middle 23 cycles and (d) the last 23 cycles.

The resistance variation shows consistency over all the cycles, averaging 115%. It can be seen in Figure 6(a) that a slight reduction of resistance variation is detected during the characterization of 5% strain. Viscoelasticity properties of the transducer may be the cause of this deviation. After the training stage, the mechanical relaxation of the yarn coming from the 20% strain deformation needs time to adapt to the reduced strain deformation. That is why this decrease in resistance variation is more remarkable at the beginning of the characterization. To highlight the phenomenon, a magnification in three zones of response of the transducer has been plotted in Figure 6 (b), 6(c) and 6(d). For the first 23 cycles, the resistance changes from 40 k Ω under stretching to 15 k Ω at releasing, as shown in Figure 6(b). For the last cycles, the resistance changes from 38 k Ω to 18 k Ω , as shown in Figure 6(d). Then, a decreasing of the amplitude of resistance variation is observed until the end of the cyclic test (Figure 6(c) and (d)). Nevertheless, the transducer fabricated shows good cyclability after training. The average *GF* of all 10000 cycles is 25. This result shows the applicability of such transducers to check the work of industrial robots which repeat continuously the same movement.

This amplification of the electromechanical response with the training stage is also shown by another two experiences with yarns from different batches of fabrication (Figure S3). According to these three tests, the average *GF* of transducers fabricated with this proposed method is 53 ± 27 . The high dispersion of the gauge factors of these 3 experiments is due to the manual fabrication of the transducers, which we think can be reduced once the protocol becomes automated. Nevertheless, these 3 experiments demonstrate with robustness that a training stage of an elastic yarn transducer is necessary to stabilize the electromechanical properties and enhance it.

The transducer without training exhibits a *GF* at 3, Figure 3(b), showing clearly the contribution of the training stage to the transducer sensitivity. Test with a training stage carried out by strain up to 17% is shown in Figure S4. It is shown that after 100 stretches at 17% of strain, the transducer's resistance variation is not stable for deformation in the 0-5% strain range, even if the *GF* has been amplified too. The consistent response of the transducer demonstrates that the 100 training cycles at a strain of 20% are adequate for the targeted 5% strain range of targeted detection. Soliciting pristine transducers could not result in a stable transducer in the 0-5% range, because structural change that will modify the resistance continuously happens. The yarns are then exposed to 0-20% strain solicitations to structure the sample with cracks which are able to deform/reform reversibly in the 0-5 % range. This phenomenon can be explained not only by the appearance of the cracks but also by the rearrangement of the multi filaments of yarn, as shown in Figure 5(b).

After each dynamic test, when the yarn returns to its initial length and the resistance variation achieved by the deformation, a longer inertial decrease of resistance is noticed. Thus, to better understand the electromechanical properties of the transducer, a test of constant elongation is carried out with another trained transducer with an initial length of 50 mm under a pre-charge force of 0.01 N (Figure 7).

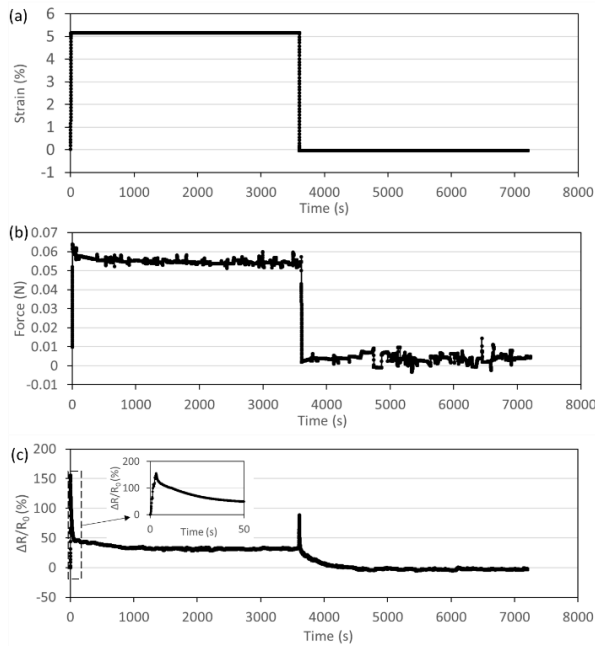


Figure 7: Test withholding at 5% of strain for 60 min and followed by releasing for 60 min, (a) strain variation, (b) force applied and (c) relative resistance.

The yarn is held for 60 min in both stretched and released states, as the strain variation demonstrated in Figure 7(a). The force applied to deform is measured during the test and shown in Figure 7(b). As the force which is applied to the transducer is so low, the measurements are noisy. To extend the yarn to a strain of 5%, a loading force of 0.06 N is required. Because of the mechanical relaxation of yarn, a slight decrease of the force of about 0.005 N is observed during the first 400 s of the holding step. After that, the force value remains constant until the release of the yarn. However, showing that creep appears by the applied force lower than 0.01 N after the release of yarn at its initial length.

An inertial effect of the resistance variation is observed. An increase of resistance of 155% is shown in Figure 7(c) because of the extension from 0 to 5% of strain. When the yarn is maintained stretched, the resistance value decreases from the peak value for about 1400 s, certainly caused by mechanical rearrangement of the functionalized layer with core yarn, and then keeps constant with evolution of 45% according to R_0 . At the beginning of the releasing step, an increase of resistance is observed, which could be explained by a spring effect. After about 1500 s of stabilization in the released state, the resistance returns to a value around R_0 . This inertial effect of resistance modification can be considered and depending on the desired dynamic of detection different values of resistance variations must be considered. For constant deformation detection, this textile yarn appears to be suitable, however, caution should be applied to check the capacity of this transducer under constant loading, because of the susceptibility of elastic material who exhibits creep.

4. Conclusion

In this study, a dip-coating method is developed to fabricate a piezoresistive transducer in the form of textile yarn. Lycra® 1880 dtex used as a base elastic substrate is covered by PEDOT:PSS with the help of PEGDA to improve the affinity between the yarn and the conductive material. This functionalization way conserves the high elasticity of Lycra® 1880 dtex so that the E of the

transducer is 3.5 MPa. Thanks to the high conductivity of PEDOT:PSS, the initial resistance of functionalized yarn is 3487 Ω for a length of 50 mm. After a training stage represented by 100 stretching/releasing cycles up to 20%, the transducer exhibits improved sensitivity due to cracks formation and is represented by an average *GF* of 25 for a strain range of 5%. Additionally, high durability is demonstrated by 10000 continuous stretching/releasing cycles with high variation of resistance. Because of the high sensitivity with a strain range under 5%, high elasticity, and durable nature of the transducer, the yarn may be used for a large range of applications. According to this research, this transducer can be used for various dynamic detections. For static deformation of the transducers with slow exchange of operational and environmental conditions, a long-term study of resistance evolution is needed. Further analysis of these transducers are necessary to calibrate its responses towards environmental conditions, because PEDOT:PSS is known for its sensitivity to humidity and temperature. Additionally, to improve the lifetime and to protect the conductive organic layer towards oxidative species and UV light, encapsulation with different coating will be studied.

Acknowledgements

We thank the French « Agence Nationale de la Recherche » for funding this research, grant #ANR-19-CE05-0004. We also thank the Filix company for supplying us graciously the Lycra® materials.

References

- [1] D. De Rossi, A. Della Santa, A. Mazzoldi, Dressware: wearable hardware, *Mater. Sci. Eng. C*. 7 (1999) 31–35. [https://doi.org/10.1016/S0928-4931\(98\)00069-1](https://doi.org/10.1016/S0928-4931(98)00069-1).
- [2] E.P. Scilingo, F. Lorussi, A. Mazzoldi, D. De Rossi, Strain-sensing fabrics for wearable kinaesthetic-like systems, *IEEE Sens. J.* 3 (2003) 460–467. <https://doi.org/10.1109/JSEN.2003.815771>.
- [3] C.E. Schmidt, V.R. Shastri, J.P. Vacanti, R. Langer, Stimulation of neurite outgrowth using an electrically conducting polymer, *Proc. Natl. Acad. Sci.* 94 (1997) 8948–8953. <https://doi.org/10.1073/pnas.94.17.8948>.
- [4] T. Yamada, Y. Hayamizu, Y. Yamamoto, Y. Yomogida, A. Izadi-Najafabadi, D.N. Futaba, K. Hata, A stretchable carbon nanotube strain sensor for human-motion detection, *Nat. Nanotechnol.* 6 (2011) 296–301. <https://doi.org/10.1038/nnano.2011.36>.
- [5] E.W. Zaia, M.P. Gordon, P. Yuan, J.J. Urban, Progress and Perspective: Soft Thermoelectric Materials for Wearable and Internet-of-Things Applications, *Adv. Electron. Mater.* 5 (2019) 1800823. <https://doi.org/10.1002/aelm.201800823>.
- [6] J. Parcell, N. Aydemir, H. Devaraj, J. Travas-Sejdic, D.E. Williams, K.C. Aw, A novel air flow sensor from printed PEDOT micro-hairs, *Smart Mater. Struct.* 22 (2013) 112001. <https://doi.org/10.1088/0964-1726/22/11/112001>.
- [7] H. Wu, C. Lahuec, F. Seguin, L. Dupont, A. Khaldi, Sensitive stretchable textile transducer based on Lycra1880/PEGDA/PEDOT:PSS, in: 2022 IEEE Sens., IEEE, Dallas, TX, USA, 2022. <https://doi.org/10.1109/SENSOR52175.2022.9967155>.
- [8] A.M. Grancarić, I. Jerković, V. Koncar, C. Cochrane, F.M. Kelly, D. Soulat, X. Legrand, Conductive polymers for smart textile applications, *J. Ind. Text.* 48 (2018) 612–642. <https://doi.org/10.1177/1528083717699368>.

- [9] X. Fan, W. Nie, H. Tsai, N. Wang, H. Huang, Y. Cheng, R. Wen, L. Ma, F. Yan, Y. Xia, PEDOT:PSS for Flexible and Stretchable Electronics: Modifications, Strategies, and Applications, *Adv. Sci.* 6 (2019) 1900813. <https://doi.org/10.1002/advs.201900813>.
- [10] N. Afsarimanesh, A. Nag, S. Sarkar, G.S. Sabet, T. Han, S.C. Mukhopadhyay, A review on fabrication, characterization and implementation of wearable strain sensors, *Sens. Actuators Phys.* 315 (2020) 112355. <https://doi.org/10.1016/j.sna.2020.112355>.
- [11] L. Wang, X. Fu, J. He, X. Shi, T. Chen, P. Chen, B. Wang, H. Peng, Application Challenges in Fiber and Textile Electronics, *Adv. Mater.* 32 (2020) 1901971. <https://doi.org/10.1002/adma.201901971>.
- [12] Z. Wang, Y. Huang, J. Sun, Y. Huang, H. Hu, R. Jiang, W. Gai, G. Li, C. Zhi, Polyurethane/Cotton/Carbon Nanotubes Core-Spun Yarn as High Reliability Stretchable Strain Sensor for Human Motion Detection, *ACS Appl. Mater. Interfaces.* 8 (2016) 24837–24843. <https://doi.org/10.1021/acsami.6b08207>.
- [13] M. Zahid, H. Anwer Rathore, H. Tayyab, Z. Ahmad Rehan, I. Abdul Rashid, M. Lodhi, U. Zubair, I. Shahid, Recent developments in textile based polymeric smart sensor for human health monitoring: A review, *Arab. J. Chem.* 15 (2022) 103480. <https://doi.org/10.1016/j.arabjc.2021.103480>.
- [14] Chen, Li, Qiao, Lu, Preparing Polypyrrole-Coated Stretchable Textile via Low-Temperature Interfacial Polymerization for Highly Sensitive Strain Sensor, *Micromachines.* 10 (2019) 788. <https://doi.org/10.3390/mi10110788>.
- [15] Q. Fan, X. Zhang, Z. Qin, Preparation of Polyaniline/Polyurethane Fibers and Their Piezoresistive Property, *J. Macromol. Sci. Part B.* 51 (2012) 736–746. <https://doi.org/10.1080/00222348.2011.609795>.
- [16] K.H. Hong, K.W. Oh, T.J. Kang, Preparation and properties of electrically conducting textiles by in situ polymerization of poly(3,4-ethylenedioxythiophene), *J. Appl. Polym. Sci.* 97 (2005) 1326–1332. <https://doi.org/10.1002/app.21835>.
- [17] N. Festin, C. Plesse, P. Pirim, C. Chevrot, F. Vidal, Electro-active Interpenetrating Polymer Networks actuators and strain sensors: Fabrication, position control and sensing properties, *Sens. Actuators B Chem.* 193 (2014) 82–88. <https://doi.org/10.1016/j.snb.2013.11.050>.
- [18] A. Lund, S. Darabi, S. Hultmark, J.D. Ryan, B. Andersson, A. Ström, C. Müller, Roll-to-Roll Dyed Conducting Silk Yarns: A Versatile Material for E-Textile Devices, *Adv. Mater. Technol.* 3 (2018) 1800251. <https://doi.org/10.1002/admt.201800251>.
- [19] E. Bihar, T. Roberts, M. Saadaoui, T. Hervé, J.B. De Graaf, G.G. Malliaras, Inkjet-Printed PEDOT:PSS Electrodes on Paper for Electrocardiography, *Adv. Healthc. Mater.* 6 (2017) 1601167. <https://doi.org/10.1002/adhm.201601167>.
- [20] Y. Ding, M.A. Invernale, G.A. Sotzing, Conductivity Trends of PEDOT-PSS Impregnated Fabric and the Effect of Conductivity on Electrochromic Textile, *ACS Appl. Mater. Interfaces.* 2 (2010) 1588–1593. <https://doi.org/10.1021/am100036n>.
- [21] E. Dazon, Y. Lin, H. Faber, E. Yengel, X. Sallenave, C. Plesse, F. Goubard, A. Amassian, T.D. Anthopoulos, Stretchable and Transparent Conductive PEDOT:PSS-Based Electrodes for Organic Photovoltaics and Strain Sensors Applications, *Adv. Funct. Mater.* 30 (2020) 2001251. <https://doi.org/10.1002/adfm.202001251>.
- [22] L. Duan, D.R. D’hooge, L. Cardon, Recent progress on flexible and stretchable piezoresistive strain sensors: From design to application, *Prog. Mater. Sci.* 114 (2020) 100617. <https://doi.org/10.1016/j.pmatsci.2019.100617>.
- [23] X. Wu, Y. Han, X. Zhang, C. Lu, Highly Sensitive, Stretchable, and Wash-Durable Strain Sensor Based on Ultrathin Conductive Layer@Polyurethane Yarn for Tiny Motion Monitoring, *ACS Appl. Mater. Interfaces.* 8 (2016) 9936–9945. <https://doi.org/10.1021/acsami.6b01174>.
- [24] M. Zhang, C. Wang, Q. Wang, M. Jian, Y. Zhang, Sheath-Core Graphite/Silk Fiber Made by Dry-Meyer-Rod-Coating for Wearable Strain Sensors, *ACS Appl. Mater. Interfaces.* 8 (2016) 20894–20899. <https://doi.org/10.1021/acsami.6b06984>.

- [25] X. Liao, Q. Liao, Z. Zhang, X. Yan, Q. Liang, Q. Wang, M. Li, Y. Zhang, A Highly Stretchable ZnO@Fiber-Based Multifunctional Nanosensor for Strain/Temperature/UV Detection, *Adv. Funct. Mater.* 26 (2016) 3074–3081. <https://doi.org/10.1002/adfm.201505223>.
- [26] S. Chen, Y. Wei, S. Wei, Y. Lin, L. Liu, Ultrasensitive Cracking-Assisted Strain Sensors Based on Silver Nanowires/Graphene Hybrid Particles, *ACS Appl. Mater. Interfaces.* 8 (2016) 25563–25570. <https://doi.org/10.1021/acsami.6b09188>.
- [27] J.R. Bautista-Quijano, P. Pötschke, H. Brünig, G. Heinrich, Strain sensing, electrical and mechanical properties of polycarbonate/multiwall carbon nanotube monofilament fibers fabricated by melt spinning, *Polymer.* 82 (2016) 181–189. <https://doi.org/10.1016/j.polymer.2015.11.030>.
- [28] A. El Zein, C. Huppé, C. Cochrane, Development of a Flexible Strain Sensor Based on PEDOT:PSS for Thin Film Structures, *Sensors.* 17 (2017) 1337. <https://doi.org/10.3390/s17061337>.
- [29] X. Feng, X. Wang, M. Wang, S. Zhou, C. Dang, C. Zhang, Y. Chen, H. Qi, Novel PEDOT dispersion by in-situ polymerization based on sulfated nanocellulose, *Chem. Eng. J.* 418 (2021) 129533. <https://doi.org/10.1016/j.cej.2021.129533>.
- [30] B.-U. Hwang, J.-H. Lee, T.Q. Trung, E. Roh, D.-I. Kim, S.-W. Kim, N.-E. Lee, Transparent Stretchable Self-Powered Patchable Sensor Platform with Ultrasensitive Recognition of Human Activities, *ACS Nano.* 9 (2015) 8801–8810. <https://doi.org/10.1021/acsnano.5b01835>.
- [31] K. Rohtlaid, G.T.M. Nguyen, C. Soyer, E. Cattan, F. Vidal, C. Plesse, Poly(3,4-ethylenedioxythiophene):Poly(styrene sulfonate)/Polyethylene Oxide Electrodes with Improved Electrical and Electrochemical Properties for Soft Microactuators and Microsensors, *Adv. Electron. Mater.* 5 (2019) 1800948. <https://doi.org/10.1002/aelm.201800948>.
- [32] U. Lang, J. Dual, Mechanical Properties of the Intrinsically Conductive Polymer Poly(3,4-Ethylenedioxythiophene) Poly(Styrenesulfonate) (PEDOT/PSS), *Key Eng. Mater.* 345–346 (2007) 1189–1192. <https://doi.org/10.4028/www.scientific.net/KEM.345-346.1189>.
- [33] A.S. Fiorillo, C.D. Critello, S.A. Pullano, Theory, technology and applications of piezoresistive sensors: A review, *Sens. Actuators Phys.* 281 (2018) 156–175. <https://doi.org/10.1016/j.sna.2018.07.006>.
- [34] A. Abed, Z. Samouh, C. Cochrane, F. Boussu, O. Cherkaoui, R. El Moznine, J. Vieillard, Piezo-Resistive Properties of Bio-Based Sensor Yarn Made with Sisal Fibre, *Sensors.* 21 (2021) 4083. <https://doi.org/10.3390/s21124083>.

Supplementary information:

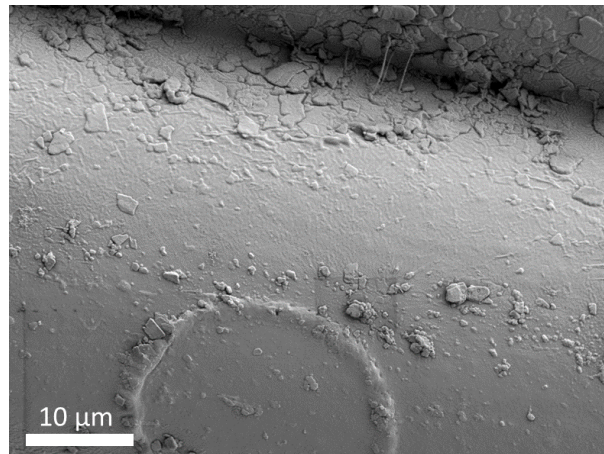


Figure S1: SEM image of washed Lycra® 1880 dtex. Evaporated DCM is observed with circular marks.

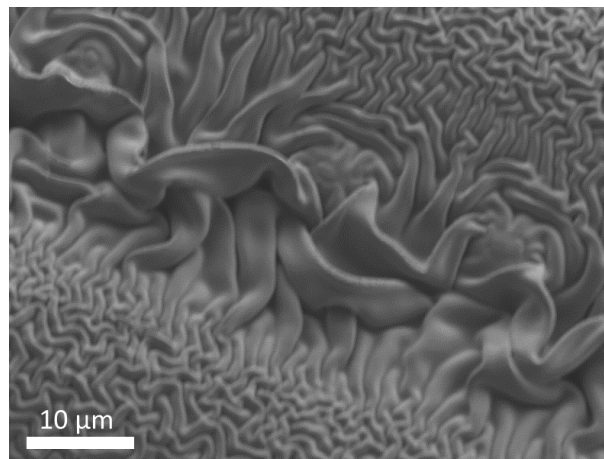


Figure S2: SEM image of yarn after polymerization of PEGDA. Polymerized PEGDA is observed not only between the filaments because of the capillarity effect, but also at the surface of filaments.

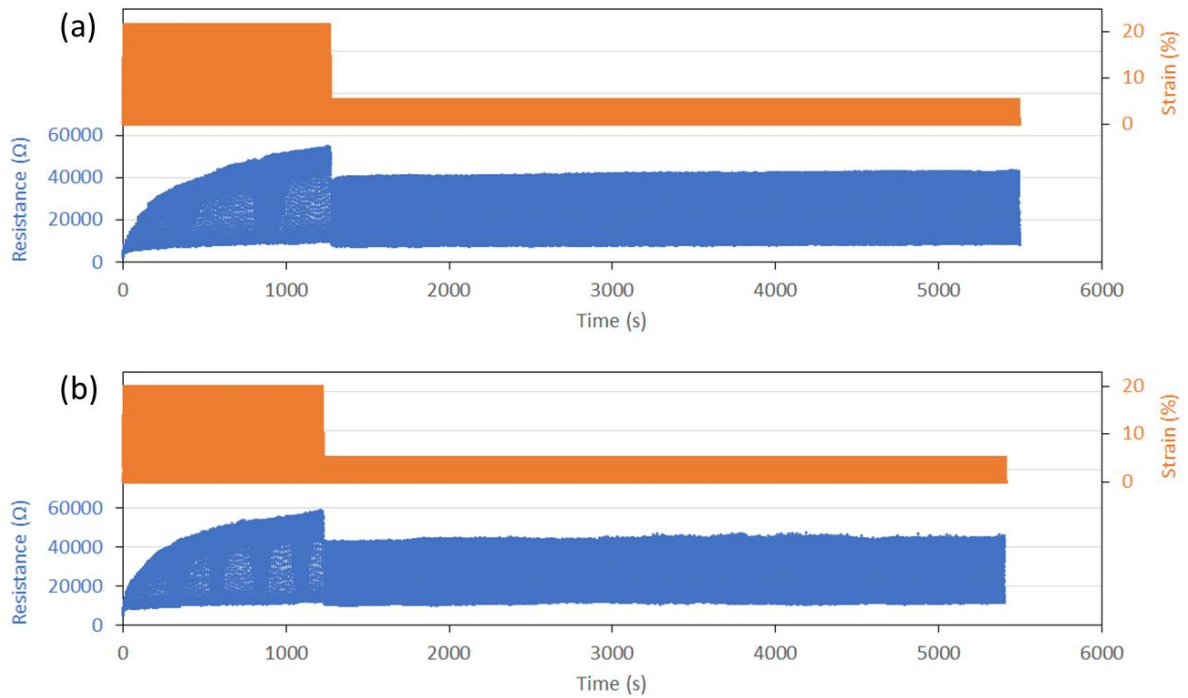


Figure S3: Two tests of electromechanical properties characterization of the transducer with training stage and at a strain of interest from 0 to 5% for 1000 cycles, with average gauge factor (a) = 80 and (b) = 54. With the same phenomenon of three tests, it is demonstrated that the electromechanical properties of the transducer are robust.

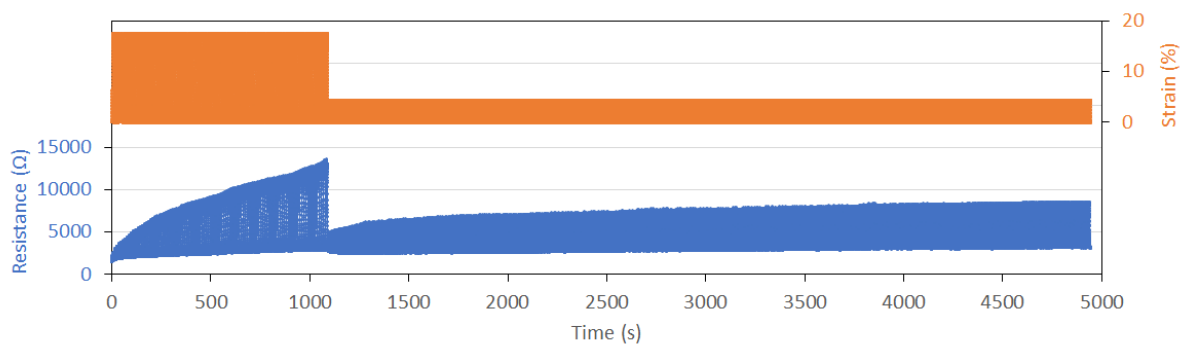


Figure S4: Electromechanical properties characterization of the transducer with training stage (strain up to 17%) and at the strain of interest from 0 to 5% for 1000 cycles. The unstable resistance variation at strain of 5% demonstrates that 100 cycles at strain up to 17% is not enough for the training stage.