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Wearable multifunctional sweat-sensing system for efficient healthcare monitoring

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ABSTRACT

Despite the huge expansion in recent years of sweat sensing and wearable technologies, several challenges are still open, including poor sample collection, separate sampling and analysis, low multi-sensing capabilities and materials toxicity. In this work, we propose a novel wearable multi-electrode platform efficiently tackling some of these issues. The sensing technology is based on one-step electrodeposited platinum nanostructures to achieve reproducibility and biocompatibility. The platform is highly flexible and includes four electrodes for the simultaneous sensing of analytes, a temperature sensor and a stable reference electrode (RE) with an ionic-liquid junction. A low-cost cotton fluidics is designed to continuously bring fresh sweat to the sensing area, while disposing the already-tested sample. The excellent analytical performance of the proposed technology is proved for different applications: Li^+ for Therapeutic Drug Monitoring (TDM) in psychiatric disorders, Pb^{2+} for the control of heavy metal contamination, K^+ and Na^+ for sport tracking. The sensors offer linear responses in artificial sweat in the ranges of clinical interest. A simulated wearable setup on a mannequin is used to test reversibility and selectivity. Finally, potassium and sodium are successfully tracked on five human volunteers during physical exercise. The accuracy of the in-situ measurements is demonstrated (Pearson coefficients of 0.97 and 0.81 for Na^+ and K^+, respectively). With its high biocompatibility, selectivity and accurate sample-handling, this wearable platform represents an important step towards the development of non-invasive monitoring devices for m-Health, paving the way for a better understanding of physiological parameters and clinical needs of each individual.

1. Introduction

Sweat sensing represents a promising alternative to the more used blood for several healthcare monitoring applications. Despite being the gold standard for the determination of chemical compounds, blood collection requires invasive procedures and qualified personnel, and it is not suitable for continuous monitoring [1,2]. Urine offers another well-established biological sample, but a longer preparation procedure is needed [3]. In addition, despite its wide use, the normalization of the sample volume is still a pending goal [4]. Possible alternative biofluids could be saliva, interstitial fluid and tears, but each of them shows some major limitations with respect to sweat [2]. Sensing in saliva is very challenging during everyday life as the concentration is strongly dependent on the most recent drinks or food intake. Furthermore, plaques and bacteria coming from food might attach on the sensor surface, thus compromising the efficiency of the system [1]. On-demand and continuous monitoring of tears is critical as the current tear collection protocols generate eye irritation and stimulate the production of reflex tears that interfere with the readings [5]. Finally, microneedles or under-the-skin excitation currents are needed to take out interstitial fluid [2]. These methods can be irritating and uncomfortable for the dermis, especially during prolonged monitoring [4,2]. On the other hand, sweat is easily accessible, it can be reproduced in the laboratory following specific standards, it does not need invasive procedures like blood sampling, it can be monitored continuously, and it provides abundance of biological information [4,6].

Every human produces about 500-700 ml of sweat per day, where several recognized biomarkers with diagnostic capabilities and good correlation with blood values are found [7]. In particular, perspiration contains electrolytes (i.e. sodium, potassium, magnesium, chloride,

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calcium), organic metabolites (e.g. urea, ethanol, lactate), trace elements (e.g. zinc, iron), amino-acids and proteins (tryptophan, interleukin 6) [7,8]. The academic literature has witnessed a 10-fold increase in this area. Both ions and other metabolites have been investigated as sweat biomarkers for different purposes over the last 5-years. Electrochemistry is the most used sensing method because of the good sensitivity, small sample volume, low cost, simple design, easy integration into microfabrication processes for large-scale production and straightforward signal interpretation [9,4,10].

In this perspective, it is clear that wearable sensors play a primary role in sweat sensing, as well as in the recent expansion of m-Health and personalized medicine. Several examples of wearable electrochemical devices have been reported in the last few years [11–16]. Nonetheless, despite the widespread research and the large amount of biological information, current wearable biosensors must still address several unsolved issues, including biocompatibility, poor collection, separate sampling and analysis, low multi-sensing capabilities [2,7]. Progress in materials science to enhance selectivity, detection range and stability is also needed. Some challenges are beginning to be tackled with the continuous progress in sensing integration and in wearable technologies, but there is still large room for improvement [7]. Recent advancements in physical sensors have enabled the commercialization of several electronics products able to measure parameters like activity, heart rate, respiration and posture. The progress in wearable chemical sensors did not show the same growth, despite the huge efforts that can be found in literature, because of the inherent challenges in handling and processing bodily fluids [2].

The innovative wearable platform proposed in this work addresses some of these challenges. The system is tested for three main areas of application:

Therapeutic drug monitoring (TDM) of lithium drug — Bipolar disorder is a severe and potentially mortal condition that consists in the alternation of episodes of manic and depressive mood. It hits every year 60 million people worldwide (World Health Organization). The risk of suicide is 30 times higher with respect to normal population [17]. It is necessary to act promptly to stabilize the patient. Nowadays the most used therapy is based on the administration of lithium salts, which we will refer to simply as lithium drug in the following discussion. However, this compound has a very narrow therapeutic range (0.8–1.5 mM) and the right dose is affected by many factors (diet, interaction with other medicines, individual variability) [18]. Overdoses could result in severe side effects including irreversible damages to liver, brain and kidneys, eventually leading to death. For these reasons, TDM of lithium drug is necessary [17–21]. Patients are thus constrained to undergo frequent check-ups in hospital, that significantly lower their quality of life, already affected by this severe condition. In particular, lithium blood concentration must be controlled at least every week at the beginning of the treatment or after any change of dose. The frequency must even be increased in the presence of any complication. Only once the optimal dose is determined, check-ups are performed every three months [22].

Lithium quantification in clinical laboratories currently requires the use of expensive techniques (e.g. atomic adsorption spectrometry or flame emission photometry) and qualified personnel [23]. In our recent work [24], we propose the innovative use of sweat sensing for lithium drug optimization to enable the non-invasive monitoring of drug levels with high accuracy from home. This is possible thanks to the good correlation between blood and sweat values. In particular, the therapeutic range in sweat corresponds to about three times the value in blood (i.e. 2.4–4.5 mM) [25]. In this work, for the first time, we fabricate a flexible and biocompatible lithium solid-contact ion-selective electrodes (SC-ISE) integrated in a fully wearable multi-sensing system for optimization of lithium drug dose.

Monitoring of lead contamination — Sweat is a promising alternative sample also in the field of xenometabolics, that is the investigation of the presence of metals in the organism due to absorption from the external environment [4]. The main sources of xenometals are food and dermal absorption [26]. Among them, lead and arsenic are one of the most harmful because of their known carcinogenic effects and their heavy repercussions on several body systems. The former is especially dangerous for the brain. Acute lead poisoning can cause pain, tingling and numbness, as well as memory and behavioural problems. All these effects can be permanent.

Lead is a trace metal in sweat in normal conditions. It can enter the human body through contaminated food, water or environment. This very toxic and dangerous element can be found in lead-based paintings, gasoline products, dust, contaminated food. Once ingested, poisoning is not immediate, but occurs over several months or even years.

Interestingly, it has been shown in some papers that lead is excreted in sweat in same or even larger amount than in urine or in blood [27,28,3]. While normal sweat levels should be below 283 μg/L, in exposed workers the amount can reach values around 17,700 μg/L [27]. Lead might come from skin adsorption when the cleaning protocols are not sufficient. Hence, perspiration analysis could represent not only an equivalent, but even a better sample biofluid than blood for monitoring of lead absorption. Despite this, current research on solid-state Pb^{2+} ISEs is very limited, thus there is large room for improvements.

Physical exercise and hydration monitoring — Perspiration is the response of our thermoregulating system, especially during physical activity. Average sweat values of about 7–95 and 3–8 mM have been found for sodium and potassium, respectively [29]. Sweating causes significant loss of water and electrolytes, that must be properly replaced through food and beverages to ensure a normal body function [30,31,29]. Therefore, electrolyte monitoring is important to avoid the risk of dehydration or unwanted damages on individual's health. This is specifically important in case of intense sport activities.

Contributions — In this work, a highly-biocompatible and efficient wearable multi-sensing system is fabricated. A general and fast technology for the accurate and simultaneous sensing of four ions is developed using biocompatible materials and fast functionalization with platinum nanostructures deposited in less than 4 min on a fully flexible custom-made platform. The proposed technology is efficiently tested in terms of analytical performance, reversibility and selectivity for three areas of applications: Li^+ for TDM of people affected by psychiatric disorders, Pb^{2+} for the control of heavy metal contamination, K^+ and Na^+ for tracking of physical exercise and dehydration. A stable and flexible Reference Electrode (RE) based on a ionic-liquid junction and a temperature sensor are also included. A low-cost cotton fluidics is integrated to ensure the continuous presence of fresh sweat on the sensing area and the disposal of the already-tested fluid, thus avoiding the recurring issues of sample handling. The complete system is successfully tested both in water and in artificial sweat, also under mechanical stress. All sensors offer linear response in the range of clinical interest. The great reversibility and selectivity of the complete wearable multi-sensing platform is demonstrated on a simulated setup with the aid of a mannequin. Finally, the wearable and biocompatible system is efficiently used to track sodium and potassium levels in five human volunteers during physical exercise. Pearson correlation coefficients of 0.97 and 0.81 are found for Na^+ and K^+, respectively, proving the great potential of the technology. A headband design is used for the testing, but the system can easily be adapted in different embodiments depending on the specific needs of the target application.

2. Materials and methods

2.1. Material

All chemicals have been purchased from Merck (Germany), unless otherwise stated. These include: H_2SO_4, $FeCl_3$, KCl, NaCl, $Pb(NO_3)_2$, LiCl, 6,6-dibenzyl-1,4,8-11-tetraoxacyclotetradecane (Li Ionophore VI), valinomycin (K ionophore I), 4-tert-butylcalix[4]arene-tetraacetic acid tetraethyl ester (Na ionophore X), tert-butylcalix[4]arene-tetrakis(N,N-dimethylthioacetamide) (Pb ionophore IV), 2-nitrophenyl octyl ether

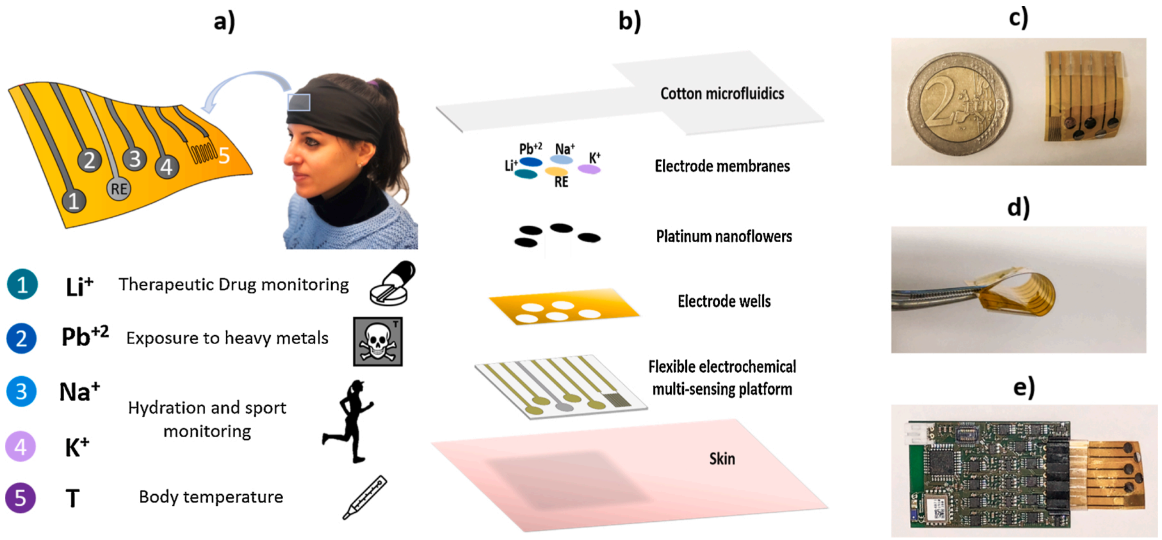

Fig. 1. Overview of the wearable multi-electrode system for healthcare monitoring in sweat: (a) example medical applications tested in this work; (b) the custom-made flexible electrochemical multi-sensing system; (c) the flexible electrochemical multi-electrode platform; (d) bending test; (e) example of interfacing with read-out electronics.

(o-NPOE), potassium tetrakis(4-chlorophenyl)borate, bis(2-ethylhexyl) sebacate (DOS), 1-dodecyl-3-methylimidazolium chloride,1-dodecyl-3-methylimidazolium chloride (IL), polyvinyl chloride (PVC), THF, NH_4Cl, acetic acid, uric acid, DL-lactic acid, ascorbic acid, glucose, pyruvic acid glutamic acid, urea.

The artificial sweat is prepared as described in [32]. Platinum screen printed electrodes with an active area of $12.56\,mm^2$ by Metrohm (Switzerland) are used for the preliminary tests of the sensing capabilities of the ion-selective membranes (ISM).

2.2. Fabrication of the flexible electrochemical sensing platform

A custom-made flexible platform on a polyimide (PI) substrate is fabricated with lithographic techniques, as described in [24]. The process flow is reported in Fig. S1. Briefly, a sacrificial aluminum layer is sputtered on top of a test silicon wafer. A PI layer is then spin-coated and two lift-off steps are performed using a plasma-activated sputtering procedure for the efficient deposition of silver and platinum. A second PI layer is deposited as passivation, and patterned by dry etching. The thin titanium layer used to protect silver from oxidation is removed by ion beam etching (IBE). Finally, an anodic dissolution step enables the release of the flexible platform from the silicon wafer.

Electrode wells are created by using a thick PI tape to avoid intermixing of the membrane cocktails and of the conditioning solutions among neighbouring electrodes (Fig. S2). The holes are created with the aid of a punch machine.

2.3. ISEs and RE fabrication

The working electrodes are cleaned by cyclic voltammetry in 0.5 M H_2SO_4 for a few cycles. The platinum nanostructures are deposited by a fast and conformal electrodeposition procedure, as described in [33]. A 10 μl drop of ISM cocktail is drop-cast on top of the electrodes and left to dry overnight. The necessary chemicals were purchased from Sigma. The precise composition of the membrane cocktails for each ISE is reported in Table S1. The electrodes are conditioned with a solution of the corresponding target ion prior to each measurements, unless otherwise stated.

The flexible Ag RE is chlorinated in 50 mM $FeCl_3$. A 10 μl drop of RE membrane cocktail consisting of 0.1% of ionic liquid (1-dodecyl-3-methylimidazolium chloride), 66% of bis(2-ethylhexyl) sebacate, 33% of polyvinyl chloride (PVC) powder dissolved in 0.5 ml of THF is drop-cast onto the electrodes and left to dry overnight.

2.4. Fabrication of the fluidic system

Different materials have been tested for the fabrication of the fluidics: fast adsorbing Whatman filter paper, wound adsorbent patches and cotton pads for make-up removal. The materials are cut in the final shape and integrated with the sensing platform by using a surgical grade tape by 3M.

2.5. Temperature measurements

The resistivity of the Pt resistor is measured using a 4-point measurement setup (Fig. S3). The probes are arranged in couples on the two distal pads. The current is forced through the two outer probes and the voltage reading across the two inner ones. This is done to achieve a more accurate resistance value, as in the 2-points measurements the contact and spreading resistances are large and the true resistivity cannot be actually separated from the measured one. The flatness of the serpentine material was confirmed by SEM analysis. The temperature is controlled using a Temptronics Model TP03215B TermoChuck system in the range 33 °C/44 °C. The actual temperature of the plate is measured with a temperature probe for hot plates. The probing current has a maximum value of 500 μA, so as to be able to perform an accurate extraction of the resistivity without altering the resistor temperature by Joule effect. For each temperature set-point, the resistivity ρ can be calculated by using the cross-sectional area, length and resistance values according to the well-known relationship $R = \rho\frac{l}{A}$.

2.6. Electrochemical measurements

IUPAC recommendations are followed for the calculations of the limit-of-detection (LOD) and of the selectivity coefficients with the separate solution method (SSM) and the fixed interference method (FIM) [34]. The conditioning procedure reported in [35] is used to obtain unbiased SSM values. A complete calibration curve is recorded towards each ion to define the Nernstian range. In the FIM the ion activity is set to 2.8×10^{-2}. All potentiometric measurements are performed in a 2-electrodes setup with an EMF6 Precision Electrode Interface. A surgical grade tape by 3M is used to fix the fluidics and the platform to the mannequin forehead to test the complete wearable sensing system.

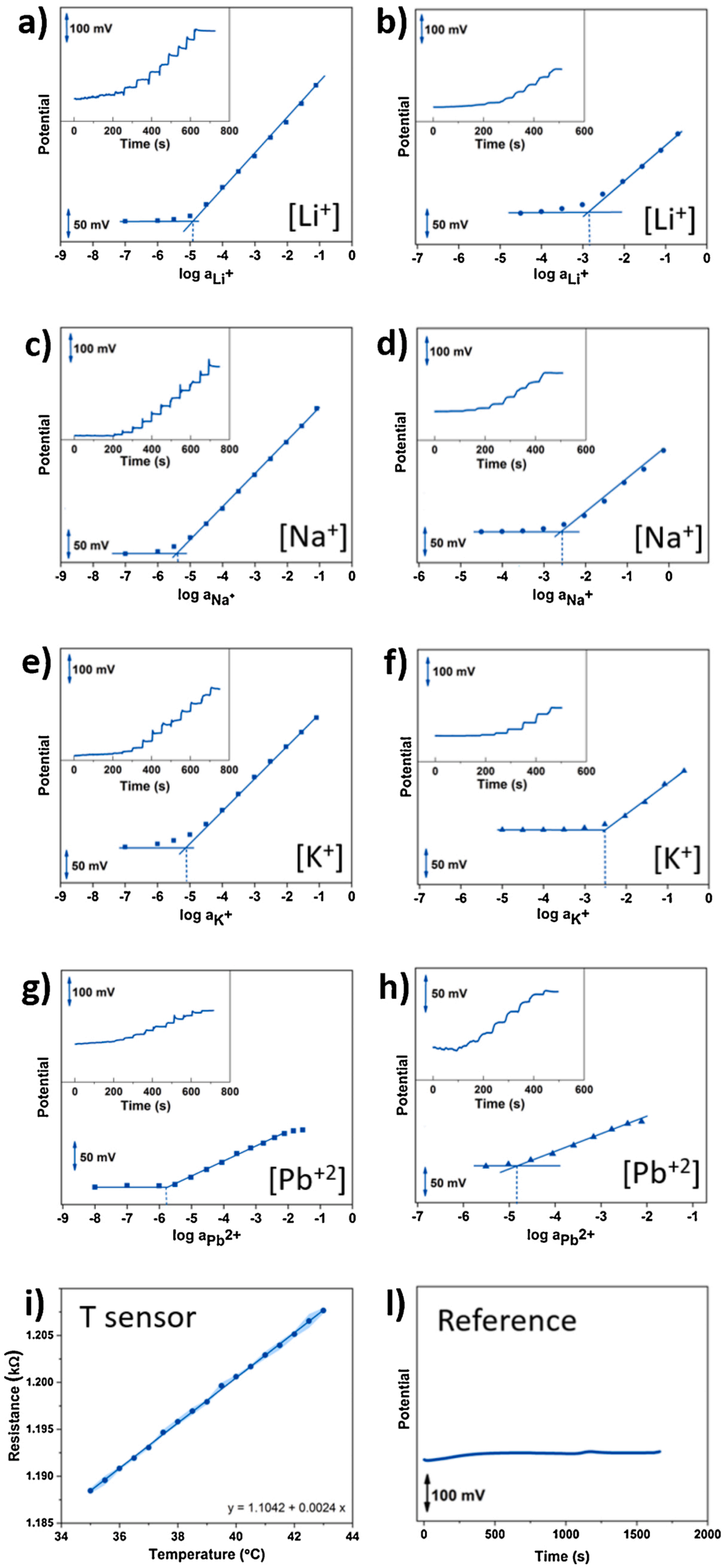

Fig. 2. (a,c,e,g) Calibrations of the different ISMs in water. (b,d,f,h) Calibrations of the different ISMs in artificial sweat. (e) Calibration of the temperature sensor. (l) Time stability in KCl 10 mM of the all-solid-state RE based on a PVC membrane doped with an ionic liquid are also reported.

Table 1
Analytical parameters of different SC-ISEs in water and in artificial sweat in comparison with literature values in water.

SC-ISE		Sensitivity [mV/decade]	LOD
Li^+	Water	58.7 ± 0.8	$(13.0 \pm 4.0) \times 10^{-6}$
	Artificial sweat	57.6 ± 2.1	$(1.4 \pm 0.2) \times 10^{-3}$
	Literature (water)	59.8 ± 1.4 [41]	5×10^{-6} [42]
Na^+	Water	56.7 ± 0.41	$(7.77 \pm 6.32) \times 10^{-6}$
	Artificial sweat	58.8 ± 1.4	$(4.13 \pm 0.23) \times 10^{-3}$
	Literature (water)	59.4 [37]	3.16×10^{-6} [37]
K^+	Water	56.1 ± 4.4	$(3.83 \pm 7.64) \times 10^{-6}$
	Artificial sweat	55.1 ± 0.9	$(3.10 \pm 0.10) \times 10^{-3}$
	Literature (water)	58.1 [36]	4.10×10^{-6} [36]
Pb^{2+}	Water	24.3 ± 3.9	$(9.31 \pm 5.57) \times 10^{-7}$
	Artificial sweat	28.9 ± 1.64	$(14.30 \pm 5.13) \times 10^{-6}$
	Literature (water)	29.1 ± 0.8 [43]	6.3×10^{-10} [43]

2.7. Testing on human volunteers

Healthy subjects aged between 21 and 45 years, have been selected for the measurements. A surgical grade tape by 3M is used to fix the wearable system to the forehead. Ex situ measurements are obtained by attaching and detaching every 5 min a small cotton patch on the skin of the volunteer.

3. Results and discussion

3.1. Testing of the flexible custom-made sensing platform

Fig. 1 represents an overview of the proposed wearable multi-sensing system and of its applications in healthcare. The platform consists of 4 ISEs with noble metals nanostructures as SCs. These materials offer exceptional potential response and stability (capacitance values of 195.3 ± 96.8 μF) with a fast one-step electrodeposition process (less than 4 min), while ensuring non-toxicity and good biocompatibility. Thus, they represent a valid and safer alternative to the more used conductive polymers and carbon-based nanomaterials.

In this work, we exploit this promising technology to build a wearable multi-sensing platform for healthcare monitoring, tackling some of the challenges of the field. Different application areas are used as examples to prove the efficiency and the wide versatility of the system, that offers high biocompatibility, reversibility and a fast fabrication route. In order to evaluate the stability and the analytical performance of the proposed SC technology, the different ISEs are tested both in water and in artificial sweat. The calibration curves of the four different target ions are reported in Fig. 2. The corresponding calibration time traces from which the curves are computed are shown in the small inset on the top left of each graph. For all ions we reached out good results both in terms of sensitivity and LOD.

The conditioning procedure is crucial to ensure proper functioning in the range of interest. For this reason, two conditioning concentrations are tested and compared for each ISE: a one day conditioning in a 1 mM solution of target analyte is performed on 5 samples, while a 10 mM solution is used for the others. The results are reported in Table S2. In general, it is possible to observe that a LOD lower of about a half-decade is achieved at low conditioning concentration, with respect to the one at high concentration, and the corresponding standard deviation is significantly lowered. The only exception is the Li^+ ISE for which the conditioning at 10 mM seems to give slightly better results. Thus, for lithium a 10 mM conditioning concentration is be used, while in all other cases 1 mM is preferred.

In Table 1 the sensing parameters of the 4 ISEs obtained in water and in artificial sweat are compared with literature values in water. Sharp steps and stable responses over time are achieved after each analyte addition. Quasi-Nernstian slopes are attained by the sensors. The presence of more interactions in artificial sweat with respect to aqueous solutions results in a slightly higher standard deviation for the sensitivity of Li^+ and Na^+ ISEs and in lower LOD values.

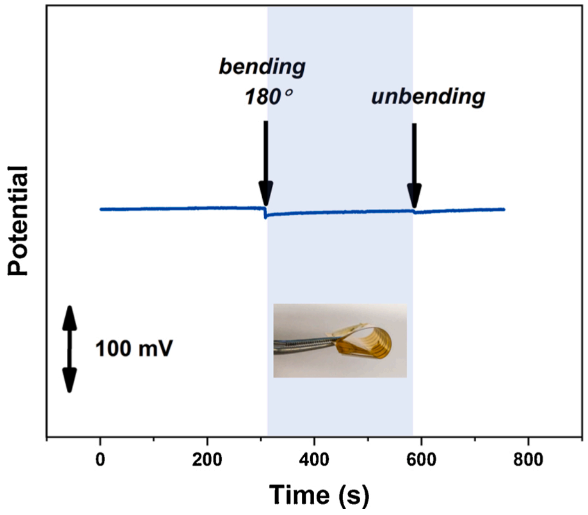

Fig. 3. Effect of bending on the potential response of the flexible Li^+ ISEs.

According to IUPAC definition, the LOD of ISEs is computed as the intersection of the linear portions of the curve [34].

The LOD of the Li^+ ISE in sweat (1.4 mM) is below the range of clinical interest of lithium drug in sweat (2.4–4.5 mM), proving the efficacy of this sensor for the target application. The LODs in water solution for both K^+ ($(3.83 \pm 7.64) \times 10^{-6}$) and Na^+ ($(7.77 \pm 6.32) \times 10^{-6}$) are similar to the ones reported in literature [36,37]. No values in artificial sweat have been found for comparison. However, the obtained LOD values in sweat ($(4.13 \pm 0.23) \times 10^{-3}$ for Na^+ and $(3.10 \pm 0.10) \times 10^{-3}$ for K^+) are well below the average physiological concentrations (51 mM for Na^+ and 5.5 mM for K^+ [29]), thus demonstrating the linear response of the sensor in the range of clinical interest. The LOD of the Pb^{2+} ISE is slightly higher with respect to the one reported in literature in water, but it is still falling in the detection range of interest. Proper tuning of the conditioning procedure or slight variations of the membrane cocktail could be exploited to achieve higher accuracy, if needed. In general, despite a few values are slightly lower than the one reported in literature, it is important to notice that our sensors are fabricated on a highly flexible and conformal platform suitable for on-skin measurements. In addition, the deposition of the nanostructures requires only 4 min and enables the achievement of high reproducibility and biocompatibility.

Together with sensitivity and LOD, selectivity is the third key parameter of every sensing technology. The selectivity coefficients of the different ISMs, calculated both with the SSM and FIM, are shown in Table S3 in comparison with the highest values reported in literature. In general, we can observe that very good selectivities are achieved, with values that are mostly well below −2. In addition, a good comparison with literature values and with conventional ISEs is found. The highest selectivity is the one towards Ca^{2+}. On the contrary, the lowest values are the ones towards K^+ and Na^+. This can be easily explained considering the small hydrated dimensions of those ions, which make interactions more probable. However, the FIM is not suitable for lead ions as the membranes do not show a linear response towards the interfering ions after conditioning in a lead-containing solution (Nernstian response towards the interfering ions is a necessary condition for the proposer use of the FIM for calibration).

The body temperature sensor consists in a resistive thermal device (RTD) made with a resistive platinum coil. RTDs offer great sensing

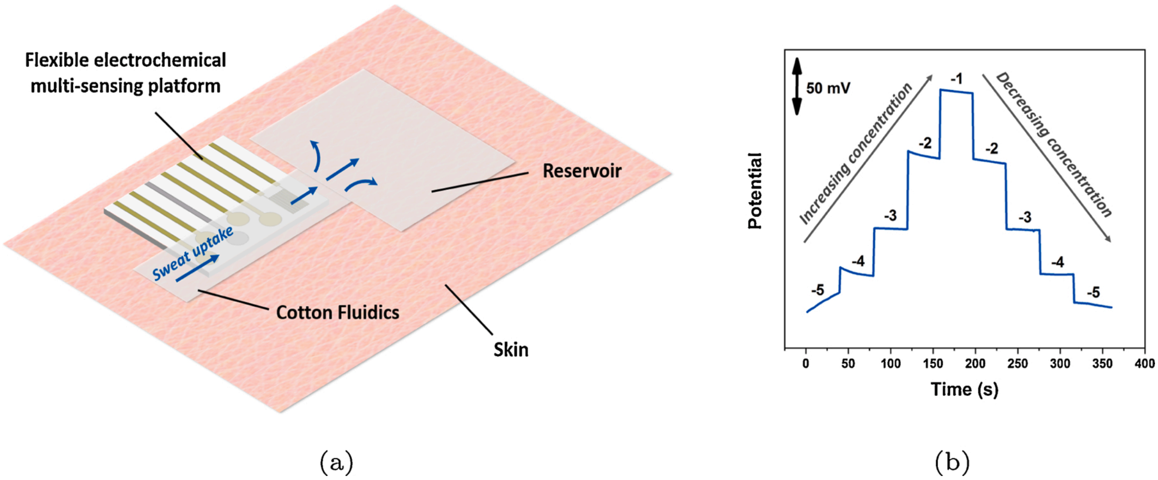

Fig. 4. (a) Scheme of the fluidics used in the complete wearable multi-electrodes system to ensure fresh sweat on the detection region and avoid direct contact of the sensors with the skin. (b) Test of the final fluidics made with make-up cotton pads while increasing and decreasing lithium concentration. The fluid is drop-cast on one side of the narrow channel in order to simulate the region where the sweat will be produced and soaked.

performance and simple fabrication for low and middle temperature applications [38]. A linear response must be found to ensure high precision. The accuracy is improved when the RTD resistance is large, otherwise the lead impedance of the device will hinder the RTD measurement. For this reason, it is important to choose the metal properly to maximize the RTD resistance. Platinum has a quite high resistivity with respect to the other conductors, and it is biocompatible, very stable and resistant to oxidation. Furthermore, it exhibits linear response. For these reasons, it is the most common material of choice together with Nickel alloys [38]. The platinum temperature sensor is designed in a serpentine with a wire width of 130 µm and 20 foldings. The calibration in Fig. 2 shows a perfect linear response in the range of interest. In addition, the resistance values are similar to theoretical ones calculated with Ohm's law (1.2 kΩ at 37 °C).

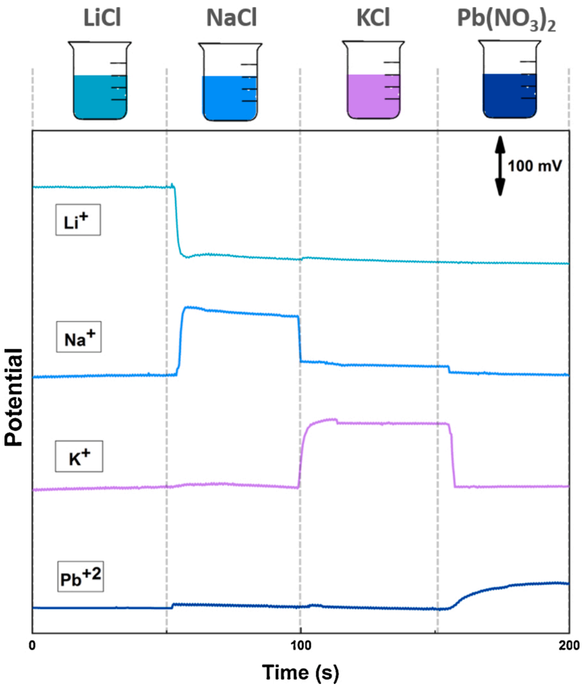

Fig. 5. Potentiometric response of each electrode of the flexible electrochemical multi-sensing platform during subsequent exposure to 10 mM LiCl, 10 mM NaCl, 10 mM KCl and 10 mM $Pb(NO_3)_2$ in artificial sweat with the simulated wearable setup.

The PVC membrane doped with an ionic-liquid is chosen for the fabrication of the flexible silver reference because of its superior stability, also at low concentrations. Fig. 2 highlights the stability over time of the flexible all-solid-state RE integrated in the multi-electrode platform proposed in this work with respect to a double junction Ag/AgCl RE. A stable RE is a crucial element in an electrochemical cell. This is especially true in potentiometric electrochemical sensors, where accurate potential readings are fundamental. In our previous work, we have tested and compared different reference membranes to improve potential stability on rigid commercial substrates [39].

3.2. Integration with a fluidic system and testing in a simulated wearable setup

As the platform is intended to be used in wearable systems, the effect of bending and unbending on the mechanical stability and electrochemical performance of the device must also be assessed. In Fig. 3 the electrochemical response of a flexible Li^+ ISEs during mechanical stress of the platform is shown. The analysis shows that the electrochemical response is practically stable during bending and unbending of 180°. In addition, no delamination phenomena are observed. Therefore, the high stability of the sensing technology also during mechanical stress is demonstrated.

An efficient fluidic system for the transport of the biofluid to the sensing area and the subsequent disposal of the already-tested sample is also crucial to ensure accuracy. This aspect is very often neglected during system design. A fluidic design with a narrow channel to collect fresh perspiration from the skin and a large reservoir to enable the disposal of the already-tested sweat is used for this purpose (Fig. 4(a)). Different low-cost adsorbing materials have been investigated: Whatman fast adsorbing filter paper, make-up cotton pads and wound cotton adsorbent patches. The adsorbing capability of each material is tested by immersing the narrow region in a Petri dish full of stained water. The reservoirs are made with different numbers of layers to increase the capacity. One, two and three layers of materials are used for the measurements. A quantitative analysis is conducted by measuring the amount of remaining liquid in each Petri dish at the end of tests. The results are reported in the graph in Fig. S4. The Whatman paper fluidics shows the slowest adsorption, as expected. It is also possible to notice that the use of multiple layers of Whatman papers in the reservoir does not contribute significantly to the increase of the capacity. This phenomenon can be explained by the considering the low adherence between different layers, as also highlighted in the initial experiments combing different grades of Whatman paper. On the other hand, the make-up cotton patch yields the highest adsorbing rate and a large increase in reservoir capacitance when multiple layers are used. In addition, it is much more compact with respect to wound patches, making it more suitable for wearable applications.

For the reasons explained before, cotton make-up patches are used for the fabrication of the final fluidic system. A surgical grade tape by 3M is used to cover the reservoir and firmly attach the narrow channel to the sensing surface. This expedient is useful both to avoid displacements and detachments of the fluidic system, and to ensure no contamination from the already tested sweat, as in this way the reservoir is isolated from the skin surface.

A potentiometric measurement at increasing and decreasing concentrations of lithium ions is performed to test the capability of the system to detect changes in concentrations without contamination. The fluid is drop-cast on one side of the narrow channel in order to simulate the region where the sweat will be produced and soaked from the skin. The successful outcome of the experiments is shown in Fig. 4(b).

The analytical capabilities and the selectivity of the complete wearable multi-sensing system are tested in artificial sweat during the subsequent exposure of the platform to 10 mM solutions of the 4 different ions. A mannequin is used to simulate the wearable setup. A headband configuration is chosen in this work, but the system can easily be adapted to the specific needs of the target application. The various solutions are added by drop-casting on the cotton fluidics by means of a pipette. The resulting potentiometric curves are reported in Fig. 5. It is possible to observe that each sensor is highly sensitive to its target ion, with sharp steps after the exposure to the corresponding ion solution. On the contrary, the signal is significantly reduced when each ISE is exposed to the solution of an interfering ion. Therefore, it is possible to conclude that the multi-sensing platform is able to detect each target ion with good accuracy and limited interference due to the presence of other ions. As expected, a small signal is present on the Na^+ curve when K^+ is added, as these two ions have similar ionic radii. However, the difference in step height is extremely significant, proving the good overall selectivity of the system.

3.3. Testing on human volunteers

The wearable electrochemical sensing platform is finally tested on human volunteers for sodium and potassium monitoring to prove the efficiency of the flexible SC technology and of the fluidics in vivo. Those two ions were chosen for the proof-of-concept human trial because they offer the possibility to perform accurate and safe experiments in university laboratories. Conversely, tests on human subjects for lithium require specific subjects under lithium therapy and extended medical monitoring. Similarly lead testing on human skin requires special monitoring for safety reasons as exposure to lead compounds is extremely hazardous.

As for the measurements with the mannequin, an headband design is chosen as the sweat rate in this region is particularly high, while

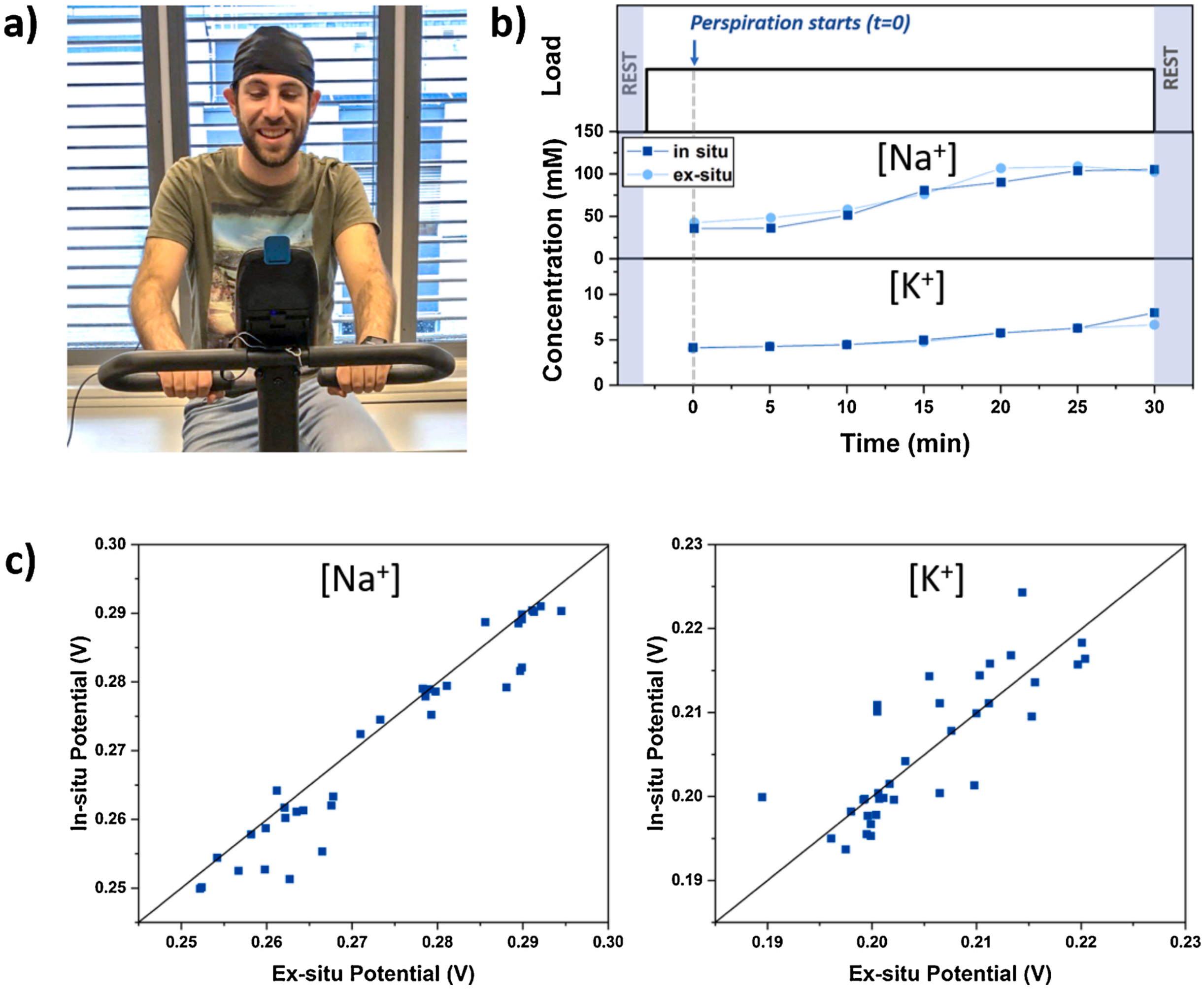

Fig. 6. (a) Experimental setup used for the testing of the wearable platform on human volunteers. (b) Potassium and sodium trends in the sweat of a volunteer during 30 min of indoor cycling after the perspiration starts. (c) Scatter plots of potassium and sodium comparing the in situ and ex situ measurements in the sweat of a volunteer during 30 min of indoor cycling after the perspiration starts.

ensuring a relatively steady and flat surface. According to the specific requirements of the target application, the system can easily be adapted to other configurations (bracelets, back patches, etc.).

The tests have been approved by the Ethical Commission of Canton Vaud. Five volunteers have been asked to cycle indoor for 30 min after the start of the perspiration. The experimental setup is shown in Fig. 6a. In situ and ex situ measurements are compared. The sampling interval is set to 5 min in order to enable the subsequent attachment and detachment of cotton pads to be used for the ex-situ measurements. It is worth to notice that this choice was made in order to have comparable results between the in situ and ex situ values. However, the system can be efficiently used also for continuous measurements with great potential stability, as proved previously with the reversibility and selectivity tests performed on the mannequin. In addition, the long-term stability of the SCs, thanks to the hydrophobic behaviour of the nanostructures that prevent the formation of a water layer, was discussed in detail in [40].

An example curve for both Na^+ and K^+ obtained from one of the volunteers is reported in Fig. 6b. The concentration of both sodium and potassium is increasing with time, as expected. In fact, as dehydration starts, there is a progressive loss of water, which causes an increase of the ionic concentrations in sweat. Similar trends have also been found on the other volunteers. All curves are reported in Fig. S5. The slight differences are easily explained considering personal physiological variability and different levels of physical training.

A good correlation between in situ and ex situ values is found for both ions in all volunteers. This result is further corroborated by observing the scatter plots reported in Fig. 6c. It is evident that a very good correlation between the potentials measured in situ and ex situ is achieved. In particular, Pearson coefficients of 0.97 and 0.81 are found for Na^+ and K^+, respectively. These results prove the great accuracy of the proposed flexible SC technology and the efficiency of the fluidics in sweat handling, paving the way for the fabrication of biocompatible and reproducible wearable multi-sensing system.

4. Conclusions

In this work, a wearable multi-sensing platform, enabling a wide range of healthcare monitoring applications and exploiting highly biocompatible and reproducible SC, is fabricated and successfully tested both in water and in artificial sweat, as well as on human volunteers. The system tackles some of the inherent challenges of current wearable technologies: it is highly reproducible and performing, it is biocompatible and enables the efficient handling of sweat sample, with a low-cost cotton fluidics that continuously brings fresh fluid on the sensing area. It includes a stable RE, a temperature sensor and four sensing sites: Li^+ for TDM of people affected by psychiatric disorders, Pb^{2+} for the control of heavy metal contamination, K^+ and Na^+ for tracking of hydration and physical exercise. The platform is highly flexible and exploits platinum SCs to avoid toxicity issues. The reversibility and selectivity of the system in artificial sweat is proved using a simulated wearable setup. Finally, the complete wearable system is successfully tested on five human volunteers to track potassium and sodium during indoor cycling. The great correlation between in situ and ex situ values is found, with Pearson coefficients of 0.97 and 0.81 for Na^+ and K^+, respectively. The use of this biocompatible and efficient platform could be extended to the measurements of several other biomarkers directly on the skin to facilitate personalized and real-time physiological investigations.

Authors' contribution

Criscuolo, Francesca: conceptualization, methodology, validation, investigation, resources, writing – original draft. Ny Hanitra, Ivan: validation, investigation, writing – review & editing. Aiassa, Simone: conceptualization, writing – review & editing. Taurino, Irene: conceptualization, supervision. Oliva, Nicolò: investigation, resources, writing – review & editing. Carrara, Sandro: supervision, writing – review & editing. De Micheli, Giovanni: supervision, writing – review & editing, project administration, funding acquisition.

Conflict of interest

None declared.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.snb.2020.129017.

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