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A novel sweat rate and conductivity sensor patch made with low-cost fabrication techniques

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***Abstract*—Sweat sensor patches offer new opportunities for unobtrusive monitoring of an athlete's physical status. This paper presents a novel sweat rate and sweat conductivity patch that is easy to prototype and can be made with common low-cost production techniques: laser cutting and standard printed circuit board (PCB) manufacturing. The device consists of a patch made from hydrophilic PET foil, a double-sided adhesive and a thin PCB with gold electrodes. Two electrodes, which are continuously in contact with the inflowing fluid, measure the sweat conductivity and a separate system with interdigitated electrodes measures the filling process of the reservoirs. Impedance measurement results of both systems demonstrate the working of the concept.**

Keywords—Conductivity sensor, Sweat rate sensor, Sweat patch

I. INTRODUCTION

Analysis of sweat biomarkers can potentially play a large role in non-invasive health monitoring. Sweat can be used for monitoring the effectiveness of medical treatment and for measuring the physical status of an athlete or people in a profession that involves a high physical workload. For example, sodium and chloride are two main constituents of sweat. Sodium and chloride levels are dependent on sweat rate and researchers suggest that elevated levels may provide information about the level of dehydration [1]. Sweat sodium and chloride levels are also main indicators in the diagnostic process of cystic fibrosis [2]. Currently, this diagnostic process is performed when the patient is in the hospital, but an unobtrusive sensor patch as is proposed in the current paper will allow to continuously monitor Na^+ and Cl^- fluctuations in home situations. This allows faster feedback on medicine effectiveness and patient well-being.

Traditionally, sweat has been an underutilized source for gathering physiological information. Therefore, little is known about inter and intra-variability of sweat biomarkers. Sweat collection and analysis involves several practical challenges, such as evaporation of the fluid and contamination of the sweat by old sweat, skin residue and bacteria [3]. Besides, biomarker concentrations can vary with body location and sweat rate [4].

A. Sweat Patches

Recent technological developments in sweat sensor patches try to solve the abovementioned problems. Several sweat rate measurement systems have been developed. Francis et al. [5] present a sensor system that can count droplets to measure low sweat rates with an amperometric system. Kim et al. [6] created a patch with an impedance sensor to measure sweat rate and a separate sensor to measure the conductivity of the fluid. The microfluidic channels are made from PDMS and the gold and copper electrodes are patterned on polyimide with photolithography. Other papers present a similar system with a different architecture and added an electrochemical sensor to measure the sodium concentration [7, 8]. The sensor patches and microfluidic systems that have been developed recently form a large step towards reliable sweat analysis. However, to fabricate those patches advanced fabrication techniques, like lithography, are required.

This paper presents a novel device for sweat rate and sweat conductivity measurement that is low-cost, robust and easy to prototype. Besides, it enables validation of the measurements by collecting the sweat in a sequence of reservoirs. After the real-time sweat measurement, the samples in the reservoirs can be used for chemical analysis in the lab. The new system is designed for use on athletes during physical exercise. The device will support physiologists in researching physiological mechanisms of sweating and engineers in validating their newly developed advanced sensor systems.

II. METHOD

A. Design

First, the sweat collection system was designed and tested in a physiological experiment. The results of this work were presented previously [9]. The collection system is made from two layers of hydrophilic foil (Visgard275 [10]) with a double-sided adhesive (3M1522 [11]) in between. Cavities are cut in the adhesive with a CO_2 laser (Lion Laser Systems, The Netherlands), which form the sequence of reservoirs. A funnel-shaped patch makes sure that the sweat drops down towards the inlet of the collection system. The collector is filled by a combination of capillary effects and gravitational effects. The reservoirs are designed in such a way that they fill consecutively, so that the samples are stored separately and can be analysed afterwards with ion chromatography. During one physiological experiment (a cycling exercise of 1 hour, average heart rate: 158 bpm, ambient temperature: 20 °C) approximately three collection systems can be filled with sweat.

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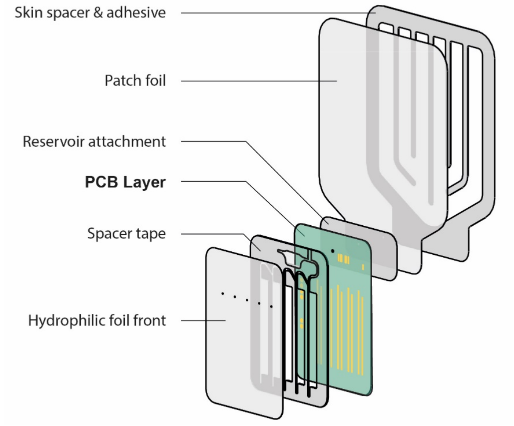

Figure 1. Exploded view of the sweat patch with integrated sweat rate and sweat conductivity measurement

TABLE I. SPECIFICATION OF MATERIALS AND CONTACT ANGLES

Materials	**Specification**	
	Carrier and Coating	***Contact angle (º) t= 10 s after contact with the surface***
Hydrophilic film (Visgard 275)	Polyethylene tereftalate and a Polyurethane matrix	50.5
Double-sided adhesive (3M 1522)	Polyethylene and Acrylate	92.2
Soldermask (Rongda H9100)	Liquid photosensitive solder resist	73.1
Gold Electrodes	Gold alloy	69.8
FR4 (KB-6160)	Glass-reinforced epoxy laminate	90.0

* Contact angles were measured with optical tensiometry (KSV Instruments Ltd)

In the new design that is presented in this paper, the back hydrophilic layer is replaced by a thin (0.6 mm) PCB (Figure 1) The used materials and their contact angles are shown in Table 1. Figure 2 shows the layout of the sensor system. Two conductivity electrodes (Figure 2, nr. 3) are placed in a reservoir in the top. The design ensures that the electrodes are covered with fluid during the entire collection process. The rounded corners of the reservoir guarantee all the liquid that enters, to flow through. Once the fluid passes the first reservoir, the bottom five reservoirs are filled consecutively. The filling process of these reservoirs is measured with interdigitated electrodes (Figure 2, nr. 5).

B. *Syringe pump experiment*

Table 1 shows that the contact angles of the materials of the PCB are significantly higher than the contact angles of the hydrophilic foil. To test whether the collector is still filling at a similar volume flow rate as the sweat rate, an experiment was executed to test the filling of the new design. The syringe pump (KDScientific 200, USA) is set at a rate of 48 µl/min. This rate is based on the collection area of the patch (40 cm^2) and an average sweat rate at the back of an athlete during intense exercise (1.2 mg/cm^2/min [12]). The pump is connected to a tube which is placed close to the inlet of the collector. The filling process is filmed to retrieve the volume flow rate.

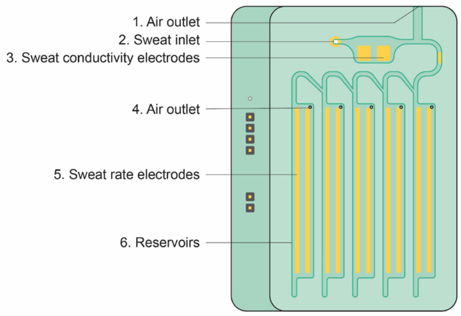

Figure 2. Layout of the sensor system (main dimensions: 70*50 mm). Sweat conductivity is measured in the top reservoir, which is filled with a constant volume of fluid. The filling process is measured with interdigitated electrodes in the reservoir sequence.

C. *Impedance measurements.*

An AD5933 impedance converter (Analog Devices, USA) is used for measuring both the filling process and the conductivity of the fluid. The chip contains a frequency generator (sweeping from 5 till 100 kHz, with an excitation signal Vpp:1 V) and the impedance is sampled with a 12bit ADC. The system performs a discrete Fourier transform to send the real and imaginary impedance to a serial interface at each frequency of the frequency sweep. This chip was chosen for the measurement because it has a digital interface and can be integrated in a wearable easily.

The conductivity sensor is tested by creating several solutions of NaCl in demineralized water (10-150 mM) and

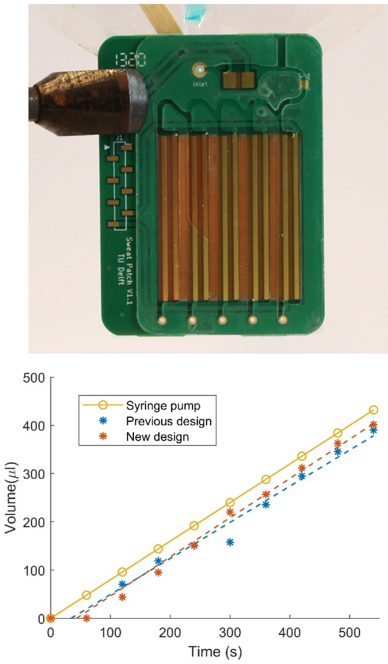

Figure 3. top: a still from the syringe pump experiment with the new design, bottom: volume flow rate of in the new design vs. the previous design

placing them in the top reservoir with a syringe. Previous sweat measurements showed that all sweat samples contained Na^+ and Cl^- concentration levels in this range.

III. RESULTS & DISCUSSION

A. *The syringe pump experiment*

The filling process of the collector was filmed with a camera. Afterwards, stills were extracted from the movie, a selection of the area that contains fluid was made and pixels are counted in each image. The pixel area was converted to volume, since the dimensions of the patch are known. Figure 3, shows the volume plotted against time. A measurement was taken every minute. A delay of around 50 s is visible, before the fluid of the pump starts entering the reservoirs. In the graph can be seen that the volume flow rate of the fluid in the new design is similar to the flow rate of the syringe pump and the old design (with two hydrophilic layers). The differences in flow rate are not significant. The camera images show that entrapment of air and formation of droplets can temporarily delay or accelerate the inflow of sweat. This emphasizes the importance of real time measurement over a timespan that is larger than several minutes, to find the actual sweat rate.

B. *Impedance measurements*

The graph in the top of Figure 4 shows the impedance magnitude of the conductivity sensor in the top reservoir when it is filled with different solutions of NaCl. The frequency sweep (5-100kHz) results show that undesired capacitances do not influence the measurement above approximately 50 kHz for all solutions. The magnitude of the impedance lies between 3.6 kΩ and 250 Ω for all measurements. The bottom graph in Figure 4 shows the average conductance for different NaCl solutions. There is a linear relationship between conductance and NaCl concentration, as expected.

To test the sweat rate sensor with the interdigitated electrodes, a separate experiment is executed. Figure 5 shows the measured conductance plotted against the volume that is present in the reservoirs. As a reference, based on the average conductance of one full reservoir (± 130µl), the expected conductance values for different volumes were calculated. The volume that is present in the supply channel and in the first reservoir (respectively ± 13.5µl and ± 70µl) were taken into account as well. The figure shows that the trend in the two graphs is fairly similar, which proves the working of this sensor system. The inset shows the corresponding resistance plotted against volume.

There is one part of the sweat rate sensor that can be improved. Because the electrodes are all connected, the difference in resistance becomes smaller when more reservoirs are filled. In the fifth reservoir it will become smaller than 1 Ω. This means that the measurements become less accurate over time during the filling process. To solve this problem, separate electrode pairs for each reservoir can be made and a multiplexer can be added in the final design. This multiplexer can enable switching between the electrodes in the different reservoirs and it can switch to the conductivity sensor in the top reservoir too. Only one impedance converter (AD5933) will be required in this case. This will be possible since the required measurement rate is relatively low and the calibration can be kept the same for both the concentration and sweat rate experiments.

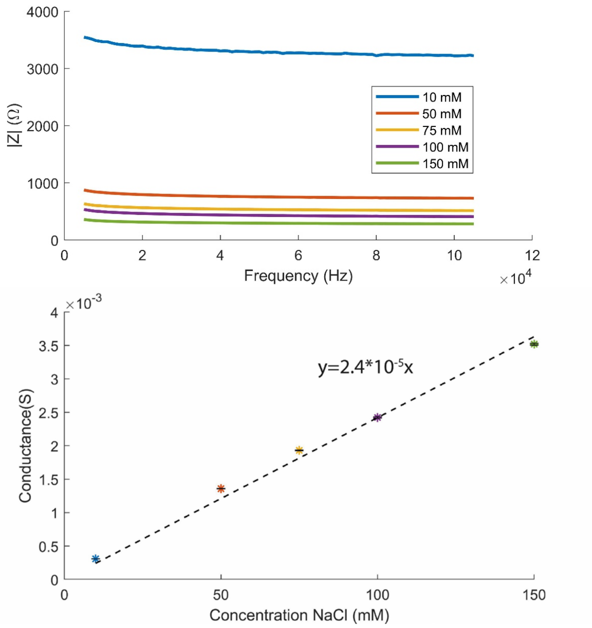

Figure 4. Measured impedance magnitude (top) and conductance (bottom) for different solutions of NaCl in the collector

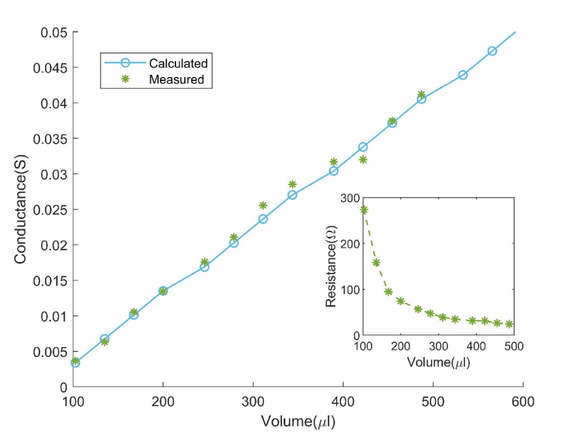

Figure 5. Measured conductance and calculated conductance (based on the mean resistance of 1 reservoir, filled with 75mM NaCl solution) for different volumes of a 75mM NaCl solution present in the reservoirs.

IV. CONCLUSION

A novel sweat rate and sweat conductivity sensor patch is presented in this paper. The new sensor can be made with low-cost fabrication techniques such as laser cutting and standard PCB manufacturing. The sweat conductivity sensor was tested and calibrated with different NaCl solutions and the sweat rate sensor proved to work when measuring different volumes of fluid. A first next step will be to perform real-time tests with the syringe pump and the sweat rate sensor. Furthermore, it is planned to make the system wearable and integrating the electronics in the patch. Afterwards, physiological experiments in a real exercise setting can be executed.

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