A Wearable Sensor for Measuring Sweat Rate

Pietro Salvo, Fabio Di Francesco, Daniele Costanzo, Carlo Ferrari, Maria Giovanna Trivella, and Danilo De Rossi

***Abstract*—Wearable sensors present a new frontier in the development of monitoring techniques. They are of great importance in sectors such as sport and healthcare as they enable physiological signals and biological fluids, such as human sweat, to be continuously monitored. Until recently this could only be carried out in specialized laboratories using cumbersome and often expensive devices. Sweat monitoring sensors integrated onto textile substrates are not only innovative but they also represent the first attempt to use such an idea in a system that will be worn directly on the body. This study outlines the development of a wearable sweat-rate sensor integrated onto a textile.**

***Index Terms*—Sweat rate sensor, wearable system.**

I. Introduction

MOST of the wearable sensors allow the measurement of parameters such as ECG, heart and respiratory rates or blood pressure [1]–[3]. There are a few biochemical sensors that are capable of measuring the composition of human sweat, such as [4] and a sodium sensor developed by CEA-Leti (www.leti.fr) for the European project Biotex. To our knowledge a sweat-rate sensor integrated onto textiles has never been described in the literature.

Different methods for water-vapor flow measurements from local skin sites have been described in [5] and [6]. They rely on the measurement of the water-vapor pressure gradient near the skin in unventilated chambers: the steeper the gradient, the higher the water evaporation rate from the skin. Indirect calculations from the weight loss are used as the reference method to estimate the average sweat rate of the whole body [7]. All these methods only allow discrete measurements (sampling rate $\sim$1 sample/minute) and require the person to remain in the same place.

In sports medicine, monitoring intense sweating in athletes engaged in strenuous training or endurance competitions could be helpful to prevent dehydration and for physiological studies aimed at optimizing performance. An opportunity to test an athlete's performance in a typical training environment is clearly an additional benefit.

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P. Salvo was with the Faculty of Engineering, University of Pisa, Pisa 56100, Italy. He is now with the Centre for Microsystems Technology, University of Gent, Gent 9000, Belgium (e-mail: pietro.salvo@gmail.com).

F. Di Francesco is with the Department of Chemistry and Industrial Chemistry, University of Pisa, Pisa 56100, Italy.

D. Costanzo and D. De Rossi are with the Faculty of Engineering, University of Pisa, Pisa 56100, Italy.

C. Ferrari and M. G. Trivella are with the National Research Council, Pisa 56100, Italy.

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The idea of possible applications in medicine and sports research prompted us to develop a wearable system allowing real-time measurements of water-vapor flow from the skin's surface. Its design resembles the open chamber approach, with two humidity sensors located at different heights from the surface of the skin.

II. Experimental

A. Theory

The skin is a complex structure, but a homogenous skin model is often assumed in order to apply Fick's first law of diffusion to analyze sweat rates [5]. Fick's first law postulates that the flow goes from regions of high concentration to regions of low concentration. Therefore, the flow is proportional to the concentration gradient. In one dimension, the first law is

$$\phi = -D\frac{\partial C}{\partial x} \tag{1}$$

where Φ is the diffusion flow $[\mathrm{mol/m^2\cdot s}]$, D is the diffusion coefficient $[\mathrm{m^2/s}]$, C is concentration $[\mathrm{mol/m^3}]$, and x is the position in one-dimensional space $[m]$. D includes the dependence on temperature. As the relative variation of D is limited, this parameter can be approximated by a constant [5]. For water-vapor at 25 °C, D is $2.49\cdot 10^{-5}\ \mathrm{m^2/s}$. The evaporation of water from any surface establishes a water-vapor concentration gradient. A quantity proportional to the difference in water-vapor concentration can then be derived by (1).

Our sweat-rate sensor is based on two humidity sensors at different heights from the skin. The difference in their responses is proportional to the vapor pressure gradient and allows the sweat rate to be measured.

In this study, sensor requirements include the following: integration onto a textiles, comfort for the user and, with the aim of keeping cost low, minimal circuitry for signal processing. Thus, since thermal conductivity humidity sensors are not wearable and resistive sensors typically need a more complex circuitry, we chose a commercial humidity capacitive sensors, Philips H1 $(\mathrm{radius} \approx 6\ \mathrm{mm}, \mathrm{thickness} \approx 20\ \mathrm{um}, \mathrm{hysteresis} \approx 3\%)$.

B. Sweat Rate Sensor

To assemble the sweat-rate sensor, a pocket was created on two fabric nets. The first humidity sensor was at a distance of 0.2 cm from the skin, while the second was 1 cm from the skin. Since sensitivity is inversely proportional to the distance between sensors, a compromise was made in order to have good sensitivity and a difference in the humidity values greater than inaccuracy in the single humidity measurements. The mesh of the net was large enough to offer negligible resistance to the diffusion of the water-vapor flow.

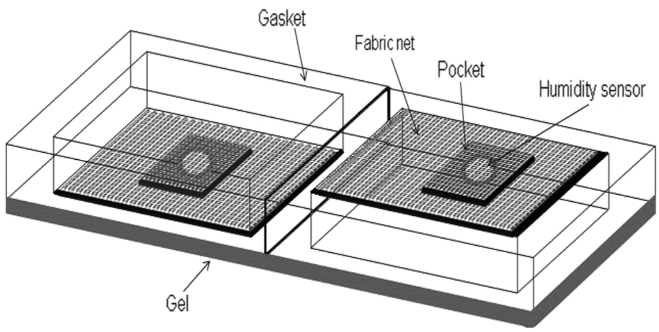

Fig. 1. Sweat-rate sensor.

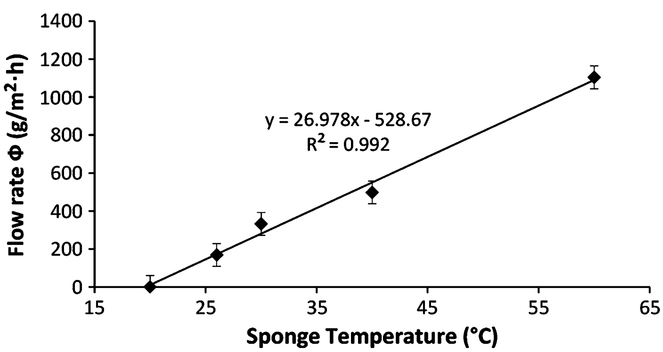

Fig. 2. Water-vapor flow from a sponge soaked in water versus temperature.

An 8×4 mm gasket was also glued to the intermediate layer to keep the sensor at the correct distance from the skin (Fig. 1). A thin sensing gel designed for ECG application (AG600 series, AmGel Technologies) was attached to the lower border of the gasket and used to fix the sensor onto the skin in order to reduce any noise due to body movements.

The main problem in calibrating the sweat-rate sensor was the preparation of a standard surface that simulated the skin and was capable of delivering a controlled flow of water-vapor at a stable rate. We decided to adopt an open chamber configuration: the flow of water-vapor was calculated using a mass balance after measuring the weight loss of a sponge soaked in water, used as an emitting surface, in a defined duration of time and at controlled temperature. The sweat-rate sensor was placed on the sponge at a height of 2 mm. The resulting calibration equation (Fig. 2), $\Phi = 115.76 \cdot \Delta C - 214.24$, was then tested in on-body tests.

III. Results

The prototype sensor was placed on the lower back since it provides a wide surface, intense sweating and is easily fitted. The sweat-rate sensor was tested on five volunteers who cycled for 25–30 min in an unventilated room kept at a temperature of 25 °C and 50% relative humidity.

Data were acquired by a wearable Bluetooth interface, equipped with a touch-screen LCD of 5.6 cm^2, a 32 bit counter, sampling rate of 10 KHz and an autonomy of 12 h, developed by CSEM (Centre Suisse d'Electronique et de Microtechnique). As a reference method, we hired a Vapometer (Delfin Technologies, Ltd.), a commercial instrument for the measurement of evaporation rates. Vapometers are currently used in many fields such as dermatology, cosmetics and personal care. It is a portable device but it is not wearable and a reset is needed after each measurement. A typical trial result is shown in Fig. 3; analogous results have been obtained in other nine trials. It can be seen that our sensor allows an almost continuous monitoring and provides data in agreement with the Vapometer, both during the exercise (the volunteer stopped cycling after approximately 25 min) and recovery. The average difference between the values of the two sensors was 4 $\mathrm{g/m^2 \cdot h}$ with a maximum of 40 $\mathrm{g/m^2 \cdot h}$.

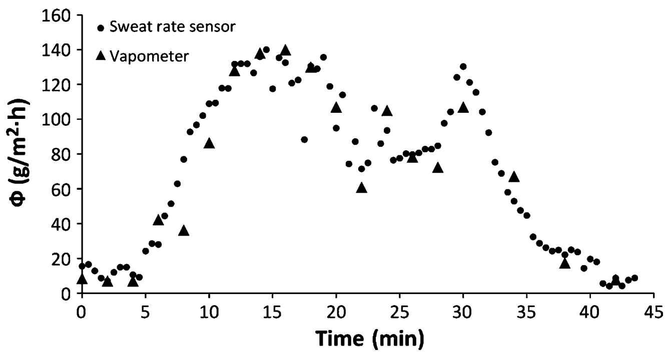

Fig. 3. Comparison between the sweat-rate sensor and Vapometer.

IV. Conclusion

We presented the first prototype of a wearable sweat-rate sensor. The sensor produces data comparable with those obtained by a commercial device used as a reference. The use of the sweat-rate sensor in open air may create problems in terms of wind, and tests need to be performed in these conditions. Possible artefacts caused by movements when the device is used in conditions other than cycling and in different positions from the lower back need to be investigated. The strong points are its simplicity, low cost, wearability, and the fact that real time measurements can be made.

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