An RFID Sensor with Microfluidic for Monitoring the pH of Sweat during Sport Activity

Alessia Riente*, Giulio Maria Bianco*, Luca Fiore†, Fabiana Arduini†, Gaetano Marrocco*, Cecilia Occhiuzzi*,
*Pervasive Electromagnetics Lab, University of Rome Tor Vergata, Rome, Italy, name.surname@uniroma2.it
†NanoBioSensing Lab, University of Rome Tor Vergata, Rome, Italy, name.surname@uniroma2.it

***Abstract*—Among the multiple healthcare applications and systems exploiting sensing RFID boards, monitoring sweat's pH can be extremely useful for sportsmen and sportswomen. Furthermore, given the multiple known benefits that sports yield, measuring pH during physical activity can be integrated with points-of-care (PoCs) for patients who need working out. This contribution details the experimental testing of an RFID sensor for measuring sweat's pH during sporting activity. The electromagnetic (EM) performances are quantified over multiple wearers, and new, low-cost microfluidics made of absorbent paper is manufactured, characterized, and tested so that the use of the tag during exercise is proven feasible.**

***Index Terms*—Biointegrated devices, body-area internet of things, electrochemical sensors, radiofrequency identification, H-IoT systems, wearable electronics.**

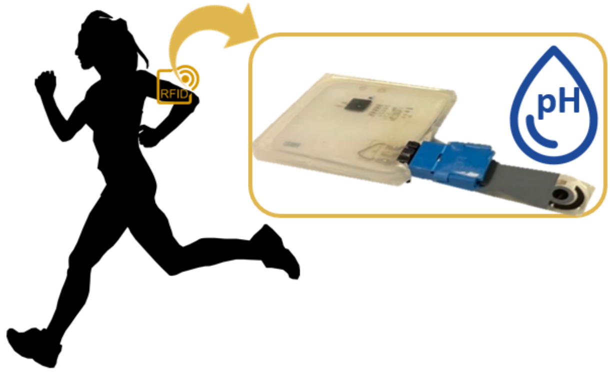


Fig. 1. Concept of a point-of-care for runners using an RFID sensor of pH.

I. Introduction

RFID devices are becoming increasingly important for healthcare according to the H-IoT (healthcare internet of things) paradigm [1]. Beyond classical asset management in hospitals [2], RFID sensors for various physical and chemical parameters are becoming more and more investigated to monitor pathological conditions [3]. These RFID sensors have the potential to become vital for the latest approaches in medical care, like, for instance, the "homespitals" [4], as to say extremely complex and advanced points-of-care (PoCs) in the patient's home [5].

The same PoC paradigm is very wide and can be employed for pursuing different scopes. Among them, sport science and analytics constitute a vital topic [6], given the important benefits that physical activity ensures [7]. Very recently, a data-logger sensing board to monitor various analytes was presented [8], and it was then upgraded to perform simultaneous sensing of pH and sodium [9]. When used in combination with NFC (Near Field Communication) patches [10], the board can be exploited to enable a large variety of PoCs to meet the more diverse needs of patients [11].

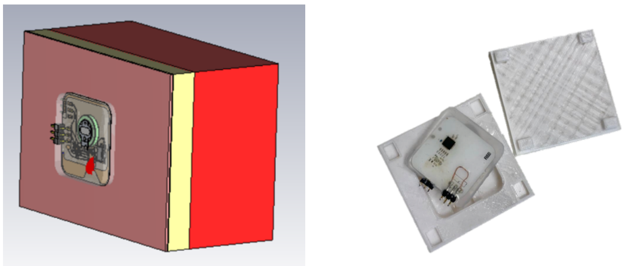
However, even though the intra-personal variability of the electromagnetic (EM) performances of the sensing tag was experimented in [9], it was preliminarily tested on a single wearer, and the inter-personal variability has never been observed. The variability is always mainly due to the local electric characteristic of the wearer's body, but the intra-personal variability is given by the different points of application, whereas the inter-personal one is caused by differences between wearers such as, for example, the body mass index. Most importantly, furthermore, under prolonged sweating, the sensing electrode returned an unstable response, and it had to be replaced since the sweat did not position itself on the sensing pad correctly when the pad was already wet. The electrode connected to the RFID tag is made of iridium oxide posed onto the working electrode surface through electrodeposition. Therefore, microfluidic channels over the electrode can address this limitation by carrying the solution to be sensed to the pad and then disposing of it [12]–[14].

In this contribution, both the shortcomings of the previous works are addressed. The reading distance of the board is measured on a set of volunteers having different body mass indexes (BMIs). Furthermore, a low-cost microfluidic made of absorbent paper is added to the sensing electrode to improve the stability of the sensor's response. The microfluidic channels enable the prolonged use of the epidermal board that was not achieved previously. The upgraded RFID board is finally tested during sports activity when the wearer cannot act on the electrode to position the sweat, and the microfluidic is essential (Fig. 1).

II. Epidermal UHF RFID Board

A. Layout and Manufacturing

The antenna of the sensor-tag is an open loop connected to the IC (integrated circuit) AMS-SL900A. The board is connected to a battery to work in battery-assisted passive (BAP) mode so that the sensitivity of the microchip (as to say, the minimum power the IC has to collect in order to activate) is -15 dBm. Two plug&play connectors are soldered to the board to enable real-time multi-sensing, and a shell made of Silbione



(a) RFID board on the multi-layer phantom.

(b) 3D-printed mold with manufactured prototype.

Fig. 2. Simulation and prototypation of the sensing tag.

TABLE I
LAYERS OF THE BODY PHANTOM FROM THE TOP WHERE THE BOARD IS CONTACTING THE PHANTOM TO THE BOTTOM WITH ELECTRICAL CHARACTERISTICS (@900 MHZ)

Layer	Thickness	Dielectric constant	Conducibility
Muscle	1 mm	55.03	0.94 S/m
Fat	10 mm	5.40	0.6 S/m
Muscle	40 mm	55.03	0.94 S/m

and Ecoflex™ guarantees adhesion to the wearer's skin. The realized gain of the board was simulated using a detailed model of the RFID tag, including the battery and a multi-layer human phantom (Fig. 2a and Table I). To manufacture the silicon shell, a 3D-printed mold was used. For further details on the layout of the board and its fabrication, see [9] (Fig. 2b).

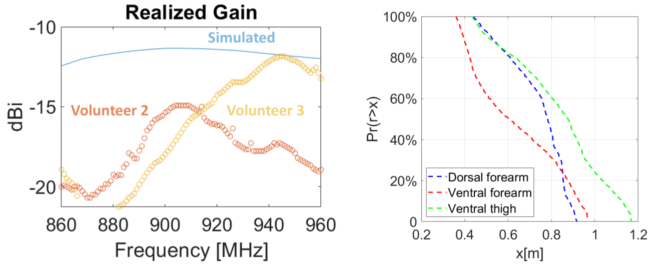
B. EM Test over Multiple Wearers

The reading distance of the board was tested over six different volunteers (resumed in Table II) to quantify the inter-personal variability through complementary cumulative distribution functions (CCDFs). For each volunteer, three positions suitable for sweat sensing [15] were tested: *i*) dorsal forearm, *ii*) ventral forearm, and *iii*) ventral thigh.

The intra- and inter-personal differences cause both a frequency shift and a variation of the optimal working frequency of the board, as depicted in Fig. 3a (point of application: ventral forearm) and Fig. 3b. Position of the sensor returning the longer reading distances was observed when the tag adhered to the ventral thigh, whereas the ventral forearm was the worst position over the test population. Overall, the CCDF(75%) reading distance was comprised between 40 cm (ventral forearm) and 75 cm (ventral thigh) when the reader (Tagformance Pro by Voyantic) was emitting 37 dBm EIRP (equivalent isotropic radiated power).

TABLE II
SEX, WEIGHT, HEIGHT, AND BMI OF THE SIX VOLUNTEERS.

Wearer	Sex	Weight [kg]	Height [cm]	BMI [kg/m^2]
1	F	57	1.54	24.0
2	F	58	1.64	21.5
3	M	72	1.72	24.3
4	M	63	1.69	22.1
5	M	72	1.75	23.5



(a) Realized gain measured on volunteers 2 and 3 and comparison with the simulated values.

(b) CCDFs of the maximum reading distances.

Fig. 3. Measured inter-personal differences.

TABLE III
RISE TIMES WITH AND WITHOUT THE MICROFLUIDICS

Solution	Without microfluidics	With microfluidics
pH 5	18 seconds	11 seconds
pH 4	14 seconds	7 seconds

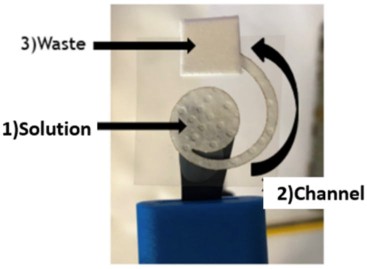
III. Microfluidic Sensor

A. Design and Functioning

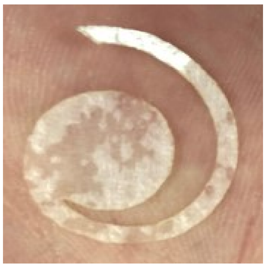
As mentioned above, in case of prolonged sweating, the sweat cannot position itself on the sensing electrode, so the potentiometric sensing is hindered. This issue can be solved through microfluidics, namely, the technology to manipulate a small amount of fluids in a confined space [16]. A microfluidic channel made of absorbent paper was conceived to carry the sweat to a waste pad in 60 seconds. The microfluidic channel is fixed to the original sensing electrode from [8], [9] to obtain a microfluidic sensor that is more stable during the measurement time (Fig. 4). Figures 4c and 4d show a test of the microfluidic sensor using food coloring to visualize the liquid flow 20 and 150 seconds after having posed the liquid on the microfluidics.

B. Characterization

The benefits of adding the microfluidic channel on the sensing electrode were quantified through bench tests by using liquids having known pH of 4 and 5. The same tag's prototype was interrogated when connected to an electrode with and without microfluidics (Fig 5). When comparing the responses from the board, it is evident that the microfluidic allows reaching faster the value corresponding to the pH of the solution, reducing the rise time computed as $5 \cdot \tau$ when modeling the rise as the charge of a capacitor (Fig. 6; numerical values in Table III). After the collection test and the comparison with the original electrode without microfluidics, the waste pad was tested as well. Both a regular and an irregular pH cycle were tested by dropping on the electrode different solutions. As depicted in Fig. 8, the cycles were correctly sensed, proving the functionality of the waste channel and pad.



(a) Sensor with microfluidic.



(b) Detail of the microfluidic made of absorbing water.

(c) Food coloring: 20 seconds after pouring.

(d) Food coloring: 150 seconds after pouring.

Fig. 4. Manufactured microfluidic sensors and test with food coloring.

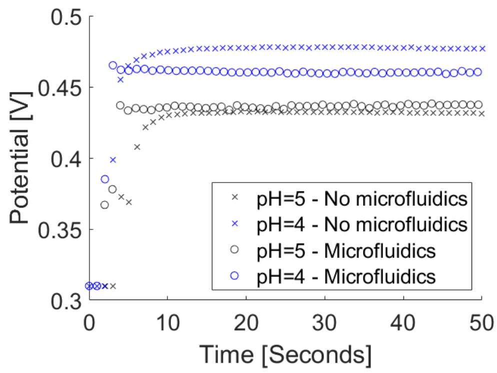
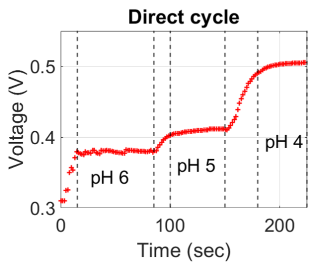
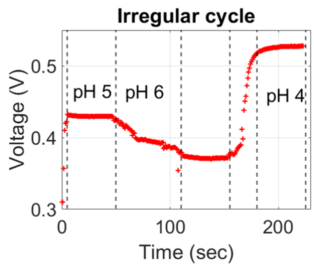


Fig. 6. Comparison of pH measurements with and without microfluidic.



(a) Direct (regular) cycle.



(b) Irregular cycle.

Fig. 7. Cycles of pH with microfluidics.

(a) RFID board with the sensor without microfluidic.

(b) RFID board with microfluidic sensor.

Fig. 5. RFID during the characterization of the microfluidic sensor. The RFID reader is a ThingMagic USB Plus,

pH, instead, was stable on a value of about 6-6.5 in both cases, as expected from the healthy volunteer not suffering from pathological conditions such as, for instance, myocardial scars [11]. Under normal homeostasis, common values of sweat pH are indeed comprised between 4.5 and 7.0 (for instance, see [8]).

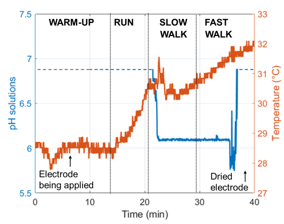
IV. Conclusion

An RFID board able to sense the sweat's pH was electromagnetically characterized in terms of intra- and inter-subject variability over five volunteers and empowered with novel microfluidics allowing for the more stable collection and waste of liquids. Overall, the board has a reading distance longer than 40 cm when interrogated with a fixed reader, the microfluidic channels made of absorbent paper enable prolonged sensing,

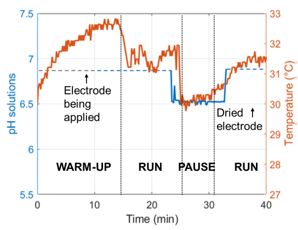
C. Measurements during Sport Activity

Lastly, the RFID tag with microfluidics was tested during sports activity. Two volunteers wore two prototypes and performed different exercise routines while the board was measuring the skin temperature and the sweat's pH in data-logger mode. Accordingly, the recording was started using an RFID reader, and data were collected by the BAP board and, finally, gathered from the IC's memory after the physical exercise with a second interrogation. The skin's temperature increased when running and decreased when stopping or sweating heavily. The

(a) Volunteer.



(b) First test.



(c) Second test.

Fig. 8. Test of the board while the wearer is walking or running.

and the RFID sensor with microfluidic is now suitable for PoC application for sportsmen and sportswomen.

We are currently working on the integration of the RFID sensor with an NFC epidermal patch [10] to create a hybrid UHF-RFID/NFC PoC [11]. The results of the ongoing work will be presented at the conference.

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