Real-time sweat analysis: concept and development of an autonomous wearable micro-fluidic platform

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Abstract

In this work the development of an autonomous, robust and wearable micro-fluidic platform capable of performing on-line analysis of pH in sweat is discussed. Through the means of an optical detection system based on a surface mount light emitting diode (smLED) and a photodiode as a detector, a wearable system was achieved in which real-time monitoring of sweat pH can be performed during sport activity. We show how through systems engineering, integrating miniaturised electrical components, and by improving the micro-fluidic chip characteristics, the wearability, reliability and performance of a sweat analysis platform has been significantly improved.

Keywords: microfluidic; smLED; photodiode; wearable.

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1. Introduction

Sweat is a body fluid naturally produced during physical exercise and emotional stress, and it is essentially a filtrate of blood plasma containing many substances such as sodium, chloride, and lactate [1]. Sweating is primarily a mechanism of body thermoregulation to avoid dangerous rise in body temperature correlated to the persons' increased metabolic rate. During this physiological process electrolytes and liquid are excreted by sweat glands [2]. Through the analysis of its composition it is possible to obtain useful information about the physiological condition of the body, providing information about the health and well-being of the individual, especially during sport activities.

Several factors correlate sweat pH with health. It is well known that sweat pH and electrolyte concentration are closely correlated [3] and changes in the pH of the skin play a role in skin diseases (such as dermatitis and acne) [4]. Moreover, it has been reported that the ingestion of sodium bicarbonate led to the increase in blood and sweat pH's [5].

Different sweat collection techniques have been employed over the years including whole body wash down technique [6], sweat collection patches [7] and a capsule inside a flexible adhesive membrane pasted onto the skin [8]. However, these techniques are not able to give real-time information about the physical condition of the body, due to a delay between sampling and analysis. Moreover, there is also a high risk of contamination of samples. Real-time sweat analysis performed during the exercise period is a great challenge due to the need for on-body fluid handling, sensor deployment and data management. Once accomplished such devices could provide immediate feedback of athlete health, giving prompt information of fluid loss and electrolyte concentrations.

Autonomous wearable sensors to monitor sport activities should consist of reliable systems capable of monitoring physical and/or bio-chemical conditions in real time. These sensors require that the sample for analysis is delivered in its active area where a signal will be engendered. Furthermore, important requirements such as low cost, flexibility, long term stability and minimal discomfort to the wearer are essential characteristics that these sensors need to satisfy. In our laboratories, as part of Biotex (http://www.biotex-eu.com/), a first generation of wearable, wireless sweat analysis system was successfully fabricated and tested [9]. The sensors were integrated into a wearable platform and a textile-based fluidic system was used to collect and deliver sweat. The colorimetric response of pH sensitive dye was detected using Light Emitted Diode (LEDs) integrated into the device holder. We also reported that by using micro-fluidic devices all the requirements for an autonomous wearable sensor to monitor sport activity could be fulfilled. In this type of devices the sensing material is embedded into the micro-fluidic channel and a passive pump system allows fluid motion through the micro-fluidic device [10].

In this paper, we present the technological achievements in performing real-time pH sweat analysis in real time from the base concept of the Biotex platform towards a miniature wearable micro-fluidic device. The reduction of electronic components size of the detection system coupled with a smart micro-fluidic chip fabrication and performance generated a fully autonomous wearable micro-fluidic platform for real-time sweat analysis.

2. The Micro-fluidic Platform

The micro-fluidic platform is made using poly(methyl-methacrylate) PMMA and PSA (pressure-sensitive adhesive) polymer sheets. A CO_2 laser (Laser Micro-machining LightDeck) system was used to cut the various polymer layers and laminated together using a thermal roller laminator. The sensing area is a piece of textile (1x1 mm) embedded in the middle of the device with a pH sensitive dye, which varies colour according to the pH of the sweat. Bromocresol Purple (BCP) dye is employed because its colour change is in the physiological pH range of sweat (pH 5-7).

A passive pump, based on highly absorbent material, was integrated with the chip, reducing the quantities of sweat necessary for the analysis (< 5μl) [10]. Figure 1 shows four pump-less micro-fluidic devices and the relation between the channel length and the time necessary for the fluid to reach the sensing area. The channel of 2 mm ensures fast sensor response reducing the delay time between the generation of the sweat in the skin and the sensor response to less than 20 s. This is a significant achievement compared to the Biotex sensor ((Fig.2(A)), where the response time was 5 minutes [11]. Moreover, since the sensing area is enclosed inside the micro-fluidic device cross contamination from other skin areas is very unlikely.

The integration of a simple cotton thread inside the micro-channel ensured a homogeneous sweat flow rate through the channels (Fig. 2(D)), improving system response time and fluid flow in the micro-fluidic device. In this system the platform robustness and dynamics during long-term sport activity was significantly improved since the length of the channel was increased two times with respect to the previous device (Fig.2(B)) ensuring flexibility and adaptability of the inlet of the micro-fluidic chip with respect to the sensor electronics.

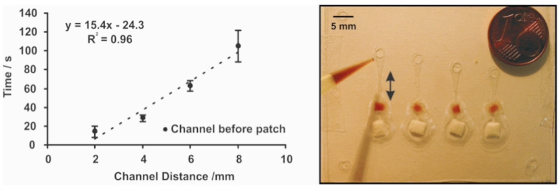

Fig. 1. Relation between channel length and the time that sweat needs to reach the sensing area using the passive pump in the chip (left), picture of four micro-fluidic devices with different channel length (right).

3. Detection system

The detection takes place by means of a photodiode and a LED placed above and below the sensing area. The colorimetric detection is performed as the sensing material changes colour according to the sweat pH. The light emitted by the LED is attenuated as it passes through the textile depending on the pH of the sample and this change in light intensity is sensed by the photodiode. Black masking tape is used to position the LED and the photodiode to block ambient light.

Despite the good performance obtained by the Biotex platform (Fig.2(A1)), a significant reduction of the detection system dimensions was achieved by replacing standard LEDs with surface mount LEDs (smLED). This reduced the bulkiness of the system electronics and produced a prototype that was more compatible with wearable applications. Initially, the smLED's were integrated in a wired configuration (Fig.2(C)), wherein both the smLED and the photodiode were controlled by a Lilypad Arduino microcontroller, which is designed for wearable applications and uses the ATmega328V microcontroller. Incorporation of an Arduino Funnel IO, which uses the same microcontroller as the Lilypad, enabled a wireless system to be realised through which data could be wirelessly transmitted to an Xbee base-station connected to a remote laptop via a USB serial link, as shown in Fig.2(E). Both systems are worn via a Velcro belt located around the pelvis of the wearer.

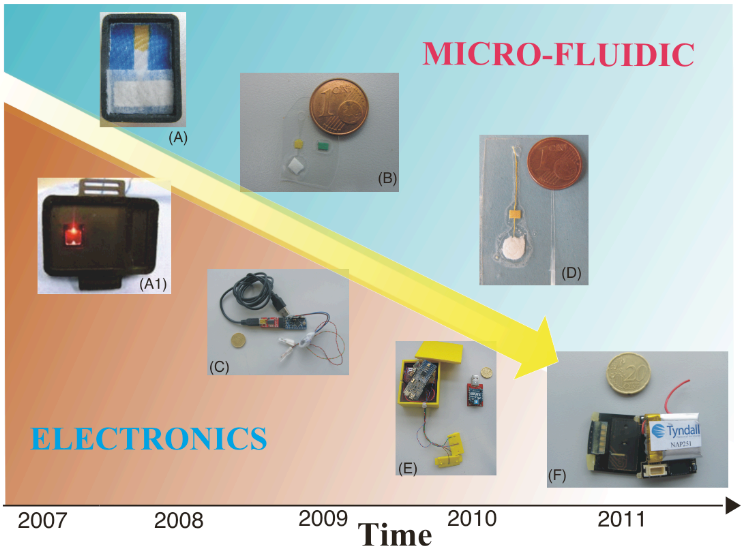

Fig. 1. Schematic of the development of the micro-fluidic and the electronics in the autonomous wearable micro-fluidic platform for sweat pH analysis. (A – A1)Biotex platform, (B)First generation of the flexible micro-fluidic chip, (C) Wired detection system, (D) Second generation of the micro-fluidic chip, (E) Wireless detection system, (F) Third generation of the wearable micro-fluidic platform.

In spite of the fact that the wireless system in the initial form (Fig.2(E)) provided improved freedom of movement, it was too big and uncomfortable to carry during the exercise period. Fig.2(F) shows the third generation of the wearable micro-fluidic device, in which all the electronic components are integrated in a much smaller cordless platform (2.5 × 3 cm) capable of wireless transmission of sweat composition data directly to a laptop. The final design opens the possibility of performing real-time sweat analysis, minimising the discomfort of the wearer while simultaneously providing information about the wearer's physiological conditions during an exercise session.

4. Conclusion

In this work we have presented significant improvements made in the realisation of a fully autonomous wearable sensor capable of performing real-time chemical analysis of sweat composition during exercise events. The micro-fluidic system was developed using low-cost and flexible materials, and the passive pump system was developed through a super absorbent material and a cotton thread inside the channel, improving robustness and dynamic response. Improvements in the detection system were gained through miniaturization of its components as such wireless platform, battery and package. All these improvements have been made in order to make a platform that was physically compatible with the needs of wearable applications, while still providing a chemical analysis capability through the monitoring of reactive indicator colour (pH in this case) using a smLED-photodiode detector.

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