# Textile sensors to measure sweat pH and sweat-rate during exercise

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*Abstract*— **Sweat analysis can provide a valuable insight into a person's well-being. Here we present wearable textile-based sensors that can provide real-time information regarding sweat activity. A pH sensitive dye incorporated into a fabric fluidic system is used to determine sweat pH. To detect the onset of sweat activity a sweat rate sensor is incorporated into a textile substrate. The sensors are integrated into a waistband and controlled by a central unit with wireless connectivity. The use of such sensors for sweat analysis may provide valuable physiological information for applications in sports performance and also in healthcare.**

*Keywords-sweat analysis, wearable sensors, smart textiles, personalised healthcare*

## I. INTRODUCTION

The primary purpose of the sweating mechanism is thermo-regulation. Throughout times of physical exertion sweat rate is increased in order to avoid a dangerous rise in body temperature caused by the persons' increased metabolic rate [1]. Monitoring sweat composition in real-time can provide useful physiological information. Sweat analysis is a valuable diagnostic tool, being the gold standard for Cystic Fibrosis diagnosis [2]. Physiological monitoring using sweat has the advantage of being non-invasive and easily accessible there are many cases where such monitoring is beneficial.

Continuous physiological monitoring of athletes during training is a vital tool in improving performance while also assessing the health status of the individual. Athletes must ensure electrolyte balance and adequate re-hydration after exercise or risk reduced performance [1, 3]. Re-hydration is a major part of the recovery process after exercise. It is well established that performance of exercise in a dehydrated state is impaired, and that both high-intensity and endurance activities are affected. There is also an increased risk of heat illness in individuals who begin exercise in a dehydrated state [4]. The concentration of electrolytes in sweat varies between individuals and therefore it would be of great advantage to develop personalized rehydration strategies depending on fluid and electrolyte losses. Another scenario where electrolyte balance is critical is in cases of extreme heat and/or physical exertion where drinking too much water can lead to hyponatremia. This is characterized by low levels of sodium and can result in symptoms such as headache, nausea, vomiting and muscle cramps. When there is a quick onset of hyponatremia, for example during prolonged exercise, it can lead to more severe complications such as seizures, coma, brain damage and death [5]. Dehydration and electrolyte balance is not only of vital importance to athletes but can seriously affect vulnerable populations, e.g. in the elderly dehydration can cause serious illness and even death particularly in the event of a heat-wave [6]. Continuous analysis of sweat may be used to detect changes in sweat composition and be used as a warning indicator.

It is known that sweat pH and electrolyte concentrations are closely related [7]. It has also been shown that sweat pH during exercise will change with the onset of metabolic alkalosis [8] which means that pH measurements may be used to relate the build-up of acid in muscle cells during exercise which leads to muscle fatigue.

While sweat may be easily obtainable, collection and measurement techniques for analysis can be awkward - Minor's method involves covering the skin with starch-iodine powder that exhibits purple dots when sweat droplets appear [9]. "Wash-down" techniques involve exercising within a plastic enclosure to collect sweat and then washing down the body within the enclosure using de-ionised water at the end of the exercise trial [10]. These methods are obviously unsuitable for long-term measurements outside of a laboratory setting. Parafilm patches have been used to create a capsule on the skin surface but these may change the sweat composition by preventing water evaporation which may block sweat gland ducts and lead to a progressive fall in sweating rates [6]. Bioimpedance measurements have been used to estimate the amount of water in the body. As a wearable system this is

challenging due to complex circuitry, measurement times [11] and the effects of movement and electrode placement [12]. to In the field, the most practical way for athletes to monitor their sweat loss is to measure changes in body weight pre- and post-exercise [13]. Therefore it is clear that a method is needed to collect and analyse sweat in an unobtrusive way in normal settings, at home, in the gym or on the track to provide real-time analysis of sweat activity.

In addition to the analysis of sweat composition for such applications, it is also of benefit to examine sweating patterns, i.e. sweat rates on different regions of the body. This may be used to identify autonomic nervous system dysfunction that may occur due to condition such as diabetes [14]. Monitoring sweat activity may also be useful in understanding and treating a condition known as hyperhidrosis which causes excessive sweating [14].

The aim of this work is to develop textile-based sensors capable of performing chemical measurements on body fluids. Sweat must be collected, delivered to the sensor surface and waste products removed. This paper presents part of the research carried out during the BIOTEX project, an EU-funded FP6 project with a consortium of 8 partners, (see www.biotex-eu.com). The goal has been to create a system that can be easily integrated into fabric and for the first time perform chemical sensing within a textile substrate.

## II. METHODS

### A. pH fabric sensor

A textile based platform with fluid handling properties is used to collect and analyse sweat samples. The design of the device is shown in Figure 1(b). The system exhibits a passive pumping mechanism, controlling fluid flow through a fabric substrate. A fabric fluidic channel is created by screen-printing an acrylic hydrophobic paste either side of the fabric. At one end of this channel is a collection "window" where sweat enters from the skin, at the opposite end of the channel a super-absorbent (SAB) material is placed to increase the capillary flow through the fabric and store the collected sweat. An acquisition layer of moisture wicking fabric is stitched in place on the skin side of the fabric patch, beneath the sensing layer. The acquisition layer in contact with the skin helps to increase the collection capacity of the device.

A pH sensitive dye is immobilised onto the fabric channel using tetraoctyl ammonium bromide. Sweat pH can range from pH 4-8, therefore the dye chosen for sweat analysis is bromocresol purple (BCP, pKa = 6.2) which exhibits a colour change from yellow to blue over this pH range. A paired emitter-detector LED configuration is used to quantify the colour change of the dye. The photo detector is a reverse biased LED and the discharge time due to stray capacitance is measured using a microcontroller. This technique has been discussed previously [15]. This technique is chosen as it is a low-power digital technique for optical detection and LEDs are versatile components that may be easily integrated into textiles. Two LEDs are embedded in silicone to prevent condensation from sweat and positioned over the fabric channel using a protective black polymethyl methacrylate
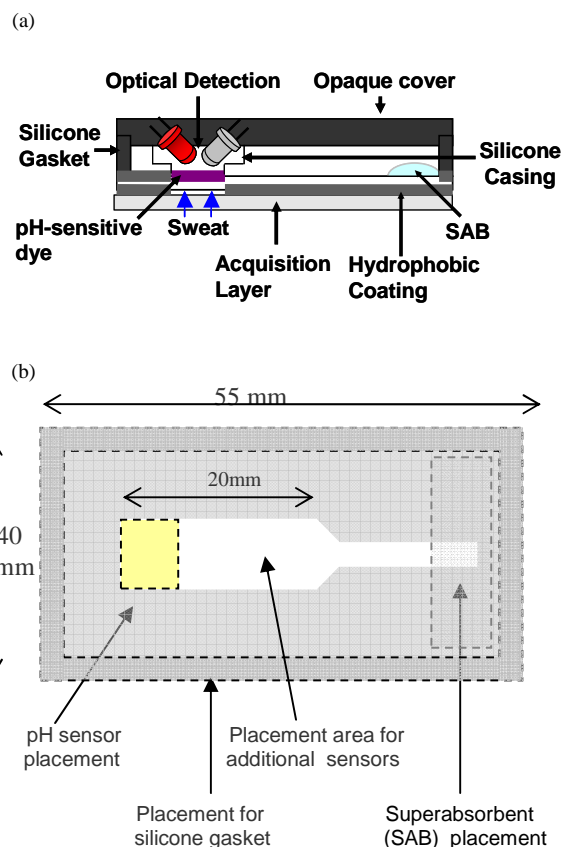


Figure 1.  a) pH sensing patch b) fabric passive pump design
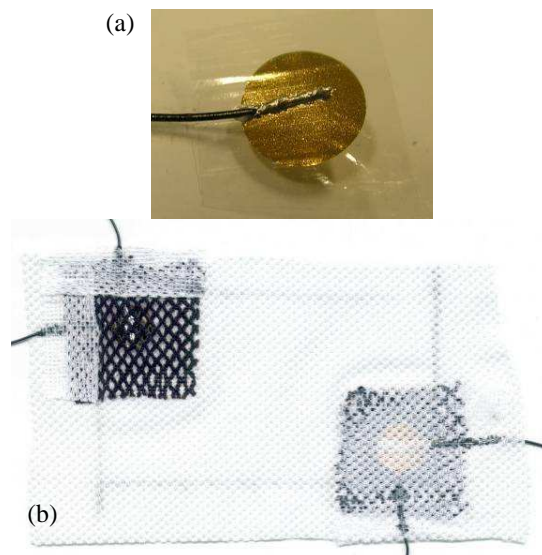


Figure 2.  a) wearable humidity sensor b) textile arrangement to measure low sweat rate values
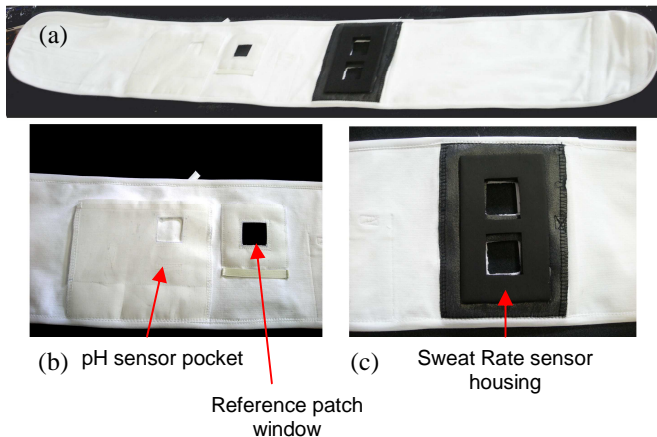
Figure 3. a) the waistband b-c) details of the housings of the pH sensing patch and sweat rate sensor
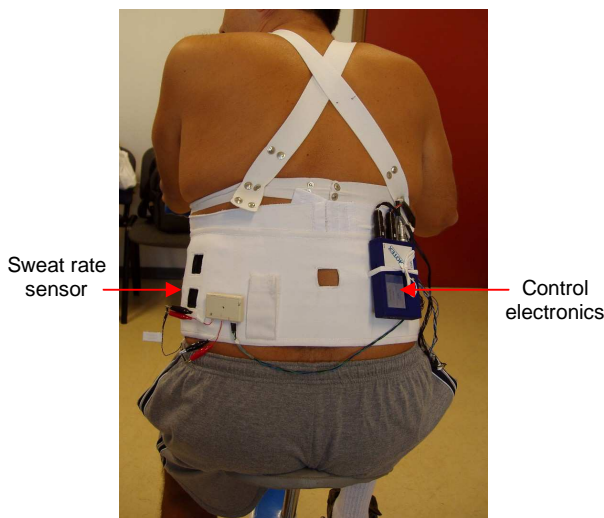


Figure 4. Experimental set-up, sweat rates sensor is positioned on the left, the pH textile patch on the right behind the control unit

(PMMA) cover held in place by a rubber gasket.

### B. Sweat rate sensor

The method used to continuously measure sweat rate is to derive its value from the gradient of humidity measured by a pair of wearable humidity sensors at two distances (0.5 and 1.5 cm) from the skin. In cases where sweat rates are low (10-40 $g/m^2$ h) more accurate estimates can be obtained by increasing the gradient. In this case, the sensor is modified by inserting a net fabric (88% polyamide, 12% elastane) between the two humidity sensors. Figure 2 shows a humidity sensor and the latter textile arrangement. The textile membrane is removed when

the measurement range has to be extended up to 1000 $g/m^2$ h. In that case, a flexible textile frame is used to place the sensors at the right positions (Figure 3). Capacitive humidity sensors are prepared either by vacuum depositing gold electrodes onto hydrophilic films (polyvinyl alcohol or cellulose acetate butyrate) or by modifying a commercial device (Philips H1) which are manufactured by a similar method.

### III. EXPERIMENTAL SET-UP

The sensors are held in place using a waistband, designed by Smartex, which ensures the fabric patch maintains good contact with the skin during exercise (Figure 3). The waistband is also used to block ambient light, which may affect the operation of the pH sensor. The waistband is made from a moisture wicking, stretch fabric for comfort with an integrated pocket to hold the pH sensing patch in place. The use of an elastic fabric laminated with a hydrophobic membrane prevents the absorption of sweat from the waistband and the reduction of the sweat flow through the pump. Hooks and loops fasteners are used to keep the passive pump and the electronics in place. This reduces motion effects during exercise.

A second pocket houses the sweat rate sensor. A neoprene frame makes sure that the right distance between sensors and skin is maintained, while holes in the pocket allow the water vapour to diffuse away without obstacles. A reference patch for pH measurements is also included in the waistband. This is used to make pH measurements via a Skincheck[TM] pH meter, which is pressed against the patch at 5 minute intervals. Reference measurements are taken once the subject is observed to begin sweating. The waistband is positioned on the subjects back so that both the pH sensor patch and the reference patch are to the right of the spine. The sweat rate sensor is positioned to the left of the spine. This is done to avoid collecting sweat which runs from the top to the bottom of the back along this hollow from other parts of the back.

The LED optical detection configuration is controlled by a central unit developed by CSEM (www.csem.ch). The detected light intensity relating to pH measurements is transferred wirelessly to a nearby laptop using a Bluetooth communication module within the central unit. The control unit also interfaces with the sweat rate sensor by measuring the capacitance of each humidity sensor. Both pH and sweat rate measurements are sampled at a rate of 0.2 Hz. The exercise set-up is shown in Figure 4. The protocol involved indoor cycling in a room at 20°C with relative humidity of 50%. Subjects were asked to cycle for up to 60 minutes at a self-selected pace.

### IV. RESULTS

Results of exercise trials on two healthy male subjects are shown in Figure 5. Sweat rate is represented by the difference in capacitance between the two humidity sensors. Sweat rate data have been normalised and smoothed using a moving average of 12 points. Figure 6 shows how the sensor signal follows the variations of the sweat rate measured by a commercial reference meter (Vapometer, Delfintech) quite well. The Vapometer is currently used in many fields such as

academic skin research and testing laboratories, personal care and chemical industries for the measurement of evaporation rates.

The temporal characteristic of sweating pattern is useful for interpreting the response of the pH sensor. A priming time is involved before the pH measurements are valid. This involves the time it takes for the subject to start sweating and for the sweat to enter the fluidic channel. This varies between individuals and depends on fitness levels and environmental conditions. The priming time is also indicated by the reference measurements as these measurements are taken once there is adequate sweat on the reference patch to wet the reference electrode. From the results in Figure 5 this priming time corresponds to the time taken to reach a constant sweat rate as measured by the sweat rate sensor. Once the sweat enters the channel it takes up to 5 minutes before a complete colour change in the pH sensitive dye is achieved. Sweat pH is observed to increase as the exercise trial progresses and as the sweat rate increases. It can be seen that for both trials there is close agreement between the results of the textile based pH sensor and those obtained using the reference method. These data have demonstrated that the performance of the textile sensor is comparable to the commercial system. Differences may be attributed to the fact that the pH sensor and reference patch are sampling sweat from separate regions of the back [7]. The increase in pH during exercise can be explained by considering the anatomy of sweat glands and their operation. Sweat glands have two main components, a tubular coiled area where the sweat is produced and the duct through which it reaches the skin surface. The primary sweat, formed in the secretory coil is near iso-osmotic, with a pH close to 7, while that excreted onto the skin is hypo-osmotic, making it acidic. It is thought that this is most likely due to ductal transport processes, which are dependent on the physiological condition [8]. The sweat becomes acidic due to

re-absorption processes which occur in the duct. However, as the subject continues to exercise, the rate at which sweat is excreted increases, in order to regulate body temperature. This reduces the amount of time available for re-adsorption processes and sweat pH increases.

## V. Discussion

Sweat is a clear hypotonic, odourless fluid containing sodium, chloride, potassium, urea, lactate, bicarbonate, calcium, ammonia, organic and non-organic compounds [16]. Clearly there are many different constituents in sweat that are inter-related. pH is a useful parameter to measure as every function of the body is dependent on our bodies maintaining a precisely balanced pH in order to function correctly. The enzyme system, as well as the electrical functions of our body, is dependent on electrolytes. Rehydration after exercise requires not only replacement of volume losses, but also replacement of the electrolytes, primarily sodium, lost in the sweat. Sweat composition not only varies among individuals but also varies with time during exercise, and is further influenced by the state of acclimatization [4]. The onset of significant dehydration is preventable, or at least modifiable, when hydration protocols are followed to assure all athletes the most productive and the safest athletic experience [17]. Therefore individual monitoring would enable personalized rehydration drinks to be prepared for each athlete to meet their needs. The design of a wearable sweat analysis system has been demonstrated as a step towards such strategies. Further trials with a wider variety of subjects in different training scenarios are needed to further validate the system.

The fabric pH sensor has been demonstrated during indoor cycling trials. To function it needs an adequate quantity of sweat entering the patch, which often takes up to 20 minutes for the person to start to sweat. Simultaneous measurement of sweat rate is useful to know when the pH readings are valid.
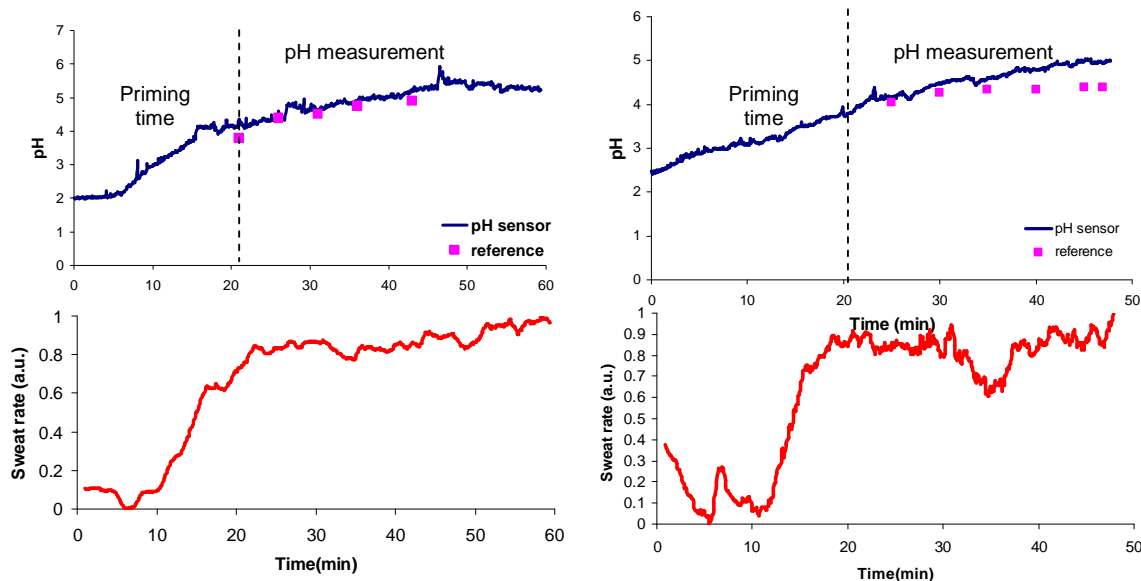


Figure 5.   Results of exercise trials on two healthy volunteers: sweat rate and pH values measured during a 60 minutes effort at self-selected pace
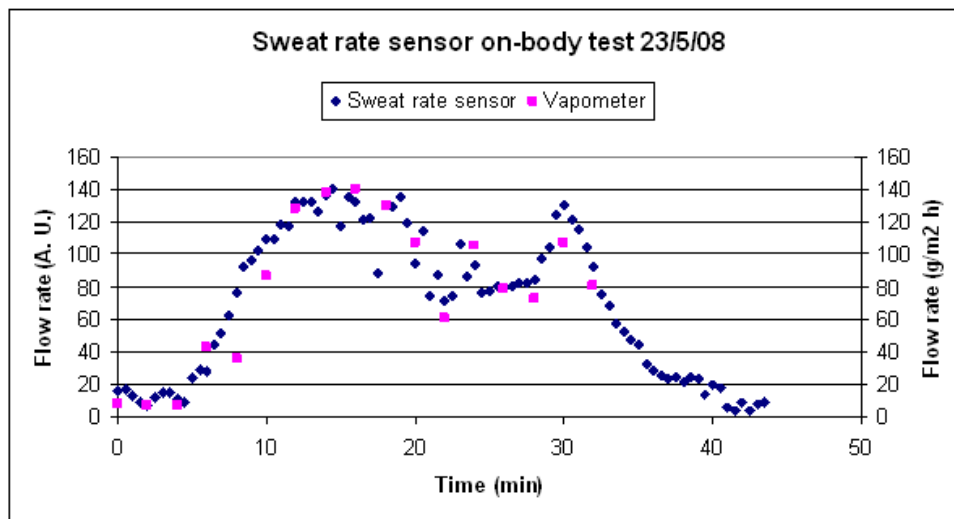
Figure 6. Response of textile sweat rate sensor compared to commercial Vapometer

The priming time of the sensor will vary depending on the individual and their sweating patterns. Future work will aim to reduce the priming time by reducing the sensor surface area where a lower quantity of sweat would be required for the reaction to occur. The dimensions of the current design were chosen to accommodate the placement of additional sensors on the channel so that more detailed analysis of sweat composition could be performed. The work presented here is just part of work involved in the BIOTEX project that tackles the issues involved in real-time sweat analysis. To get a complete picture the overall BIOTEX system includes sodium, chloride and sweat conductivity sensors along with measurement of other physiological parameters such as breathing, heart rate and blood oxygen saturation. The sweat sensors may provide complimentary signals to ECG and respiration data which have already been demonstrated using textile sensors [18, 19] to form a complete wearable healthcare monitoring garment. By developing textile sensors, the sensing elements can be easily integrated and distributed throughout a garment. This means that to study sweating activity patterns the sweat rate sensors could be placed at different regions of the body which may assist in diagnosis and treatment of illnesses affecting the autonomic nervous system. The great advantage of textile sensors is that they enable long term monitoring of the wearer at home, in normal situations.

## VI. CONCLUSIONS

Textile based sensors to measure sweat pH and sweat rate during exercise have been demonstrated. Further work is needed to relate the sweat rate measurements with flow rates. This could provide valuable information to athletes regarding their rehydration needs and also in clinical applications for treatment and diagnosis of conditions such as hyperhydrosis. The temporal response of sweating patterns provided by the sweat rate sensor has been useful in interpreting the response of the fabric pH sensor which needs adequate sweat rates to function effectively. Further work is needed to investigate other constituents of sweat such as electrolyte concentrations and also investigation of different training regimes in different environmental conditions. Analysis of these different parameters should help to understand the sweating mechanism and open a new area of research as a non-invasive approach to physiological measurements.

This area of research is unfortunately lacking due to the difficulty in sampling sweat. It is hoped that this system will open a new avenue of research allowing physiologists to explore the benefits of non-invasive sweat studies. Textile sensors in contact with the skin offer much promise to provide novel physiological information. The textile based fluid handling system that has been developed provides a platform for implementing wearable biological and chemical sensors. Garments integrating such textile sensors allow innocuous monitoring of the health and well-being of their wearers. This has many applications in sports performance and also in healthcare.

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