

# Bio-sensing Textiles for Real-time Chemical Analysis of Body Fluids

Deirdre Morris<sup>#1</sup>, Benjamin Schazmann<sup>#2</sup>, Yangzhe Wu<sup>#3</sup>, Shirley Coyle<sup>#4</sup>, Sarah Brady<sup>#5</sup>, Jer Hayes<sup>#6</sup>, Conor Slater<sup>#7</sup>, Cormac Fay<sup>#8</sup>, King Tong Lau<sup>#9</sup>, Gordon Wallace<sup>\*10</sup> and Dermot Diamond<sup>#11</sup>

<sup>#</sup>National Centre for Sensor Research, Dublin City University, Glasnevin, Dublin 9, Ireland

<sup>1</sup>deirdre.morris@dcu.ie

<sup>2</sup>Benjamin.schazmann2@mail.dcu.ie

<sup>3</sup>yanzhe@uow.edu.au

<sup>4</sup>shirley.coyle@dcu.ie

<sup>5</sup>sarah.brady4@mail.dcu.ie

<sup>6</sup>jer.hayes@dcu.ie

<sup>7</sup>conor.slater@dcu.ie

<sup>8</sup>cormac.faye@gmail.com

<sup>9</sup>kim.lay@dcu.ie

<sup>11</sup>dermot.diamond@dcu.ie

<sup>\*</sup>Intelligent Polymer Research Institute (IPRI), University of Wollongong, Wollongong NSW 2522, Australia

<sup>2</sup>gordon.wallace@uow.edu.au

**Abstract**— A wearable fluid handling platform based on polyamide lycra<sup>®</sup> has been developed for non-invasive, real-time biochemical analysis of bodily fluids. Main challenges include sample collection and delivery, sensor integration and waste sample handling. The system is able to collect sweat as it is expired through the skin and transports it through a channel defined in the fabric using a hydrophobic membrane. A super-absorbent material is placed at the end of the channel to provide continuous sample delivery and storage. A colorimetric sensor is fabricated directly on the textile channel to determine the changes in sweat pH. This is coupled with a wireless optical sensor integrated into the cover of the fluidic platform to measure colour change. Sodium and conductivity sensors have also been developed. This textile based sensing system has applications in personal health and for the analysis of sports performance and training.

## I. INTRODUCTION

Clothing has traditionally been used for a number of purposes such as protection from elements like cold and damp, for ornament and for modesty [1]. Apart from these passive uses, fabrics are also utilized in industrial and diagnostic applications, supplying moisture to a certain processes or transporting a sample to the measurement site [2], [3]. In this case, the transport of liquid through the fabric is of vital importance.

When no external forces are present, the movement of liquid through fibres is due to capillary forces which are caused by wetting of the surface [4]. Two other terms are also of critical importance in determining fluid movement; these are “wickability” and “wettability”. The first term relates to a fabric’s ability to sustain capillary flow and the latter determines how a fibre will behave when brought into contact with a liquid substance [5]. According to Ramachandran et. al, wicking will only occur on wetted fabrics and depends on the

contact angle between the fabric surface and water molecules in addition to the viscosity of the liquid [6].

In this paper, the development and testing of a fluid handling system for the real time collection and biochemical analysis of sweat is presented. The system is based on the use of a fabric which can collect sweat and transport it along a pre-defined channel. Sensors are placed along this channel and can be used to measure parameters such as pH, conductivity and sodium concentration. It is thought that this system could be integrated into clothing worn by athletes and the general population, providing a non-invasive wireless method of obtaining information on the person’s physiological condition.

In terms of personal health, sweat analysis can give information on changes in the amount of certain molecules and ions excreted due to pathological disorders [7] This can be useful in determining the best method of treatment and also for preventative medicine.

In the case of sports performance and training, sweat composition can change as a result of lack of fluids. It is well known that a visible reduction in performance will occur for a 2 % drop in body weight due to dehydration. Water loss can also lead to irritability, headache, dizziness, cramps, vomiting, increased body temperature and heart rate, increased perceived work rate, reduced mental function, slower gastric emptying [8].

As a result, analysis of parameters such as pH and sodium levels can assist athletes in developing personalized hydration strategies to maximize performance. It has previously been shown that sweat pH during exercise will change with the onset of metabolic alkalosis [9]. Therefore, real-time pH measurements in sweat may provide a non-invasive method of relating the build-up of acid in muscle cells during exercise.

This work outlines the development and testing of a fluidic platform used for sample collection and transport. Initial results from the integration of the pH, sodium and conductivity sensors are also included. The work is part of an EU funded project known as BIOTEX (Bio-sensing textile for health management) aiming to develop dedicated biochemical-sensing techniques to monitor body fluids via sensors distributed on a textile substrate, see [www.biotex-eu.com](http://www.biotex-eu.com).

## II. FLUID HANDLING PLATFORM

The most important factor in the design of the fluidic channel is developing a system which will match the rate at which sweat is excreted by the subject being examined. A study by Patterson et. al on the sweat rate of human males has shown that there is a definite regional variation in this value. It was decided to locate the fluidic platform at the lower back where the sweat rate was measured to be  $0.85 \pm 0.41 \text{ mg cm}^{-2} \text{ min}^{-1}$  [10].

As previously discussed, the choice of material will greatly influence the rate of fluid movement through the system. It is known that hydrophilic open-mesh fabrics are best for top-fill and end-fill strips using in diagnostic strips, while close-weave fabrics are good choice where uni-directional conductive paths are required [3]. In this work, a polyamide lycra® blend, commonly used for the fabrication of sports garments has been used as the platform for a fluid handling system. The material has inherent moisture wicking characteristics and is supplied by Sofileta ([www.sofileta.com](http://www.sofileta.com)).

The direction of flow is controlled by printing a fluidic channel measuring  $7 \times 20 \text{ mm}^2$  at the inlet and  $2 \times 20 \text{ mm}^2$  at its end. It is defined by screen-printing an acrylic hydrophobic paste on either side of the fabric. Following this a polyurethane film is affixed to the back or skin-side of the patch, leaving an area measuring  $7 \times 8 \text{ mm}^2$  exposed. This is the inlet through which sweat enters the channel. The pH, sodium and conductivity sensors are also placed in this region as shown in Fig. 1.

The fabric patch covers an area of  $55 \times 40 \text{ mm}^2$  and to maximize sweat collection during on-body trials an acquisition layer is placed on the skin side and acts to transport sweat towards the inlet of the fluidic channel.

A super absorbent (SAB) material is placed at the end of the channel and used to continuously draw liquid from the source or skin surface and store it. It acts as a passive pump and is an important factor in determining fluid flow.

The absorbent (Absorbtex) is supplied by Smartex ([www.smartex.ie](http://www.smartex.ie)) and has a free swell capacity of  $25 \text{ g/g}$  and a basis weight of  $172 \text{ g/m}^2$ . To obtain 2 hours operation at an average sweat rate of  $17 \text{ mg/min}$  the pump must be able to collect  $2 \text{ g}$  of sweat. Therefore,  $80 \text{ mg}$  of Absorbtex is required, which is equivalent to  $4.65 \text{ cm}^2$  or a space measuring  $15 \times 30 \text{ mm}^2$  at the end of the channel.

A rubber gasket supplied by Thuasne ([www.thuasne.com](http://www.thuasne.com)), is placed around the fabric patch. This is used to mount the

cover containing the LEDs for the pH sensor as described in section III. It is also serves to block any ambient light.

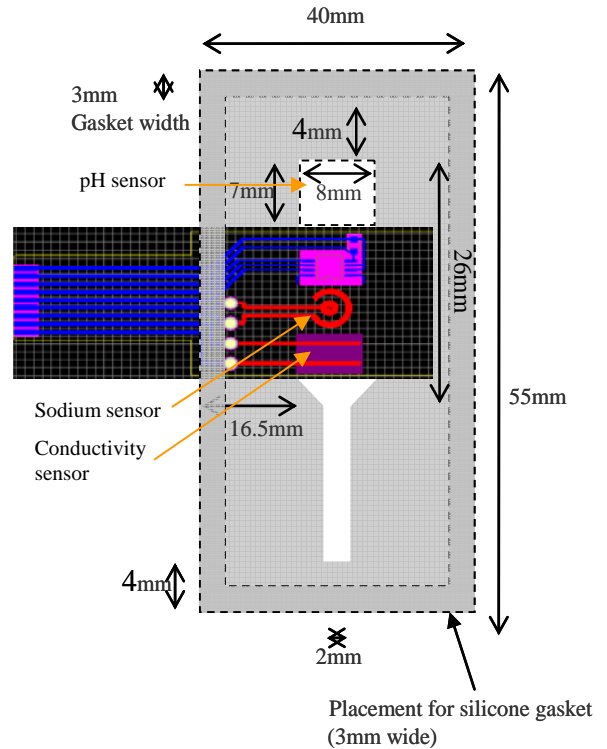


Fig. 1. Layout of fluid handling system and position of pH sensor.

### A. In-vitro testing

Once the design was finalised a number of in-vitro tests were carried out in order to verify that the pump was operating correctly. This was done using the experimental setup illustrated in Fig. 2. A fabric strip connects the reservoir filled with deionized water to the fluidic channel which has been placed on a balance so that the amount of liquid absorbed by the system can be measured. In addition, the absorbent is weighted before and after the trial in order to determine how much liquid is absorbed. Dividing this by the length of the trial allows the flow rate through the fluidic channel to be estimated.

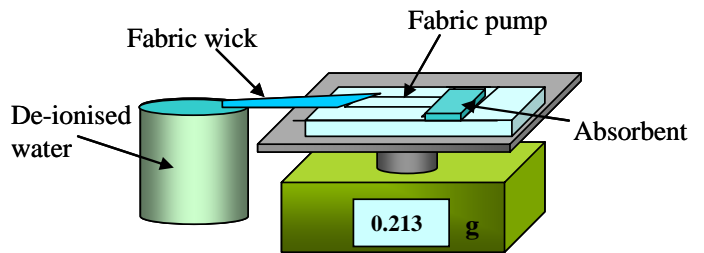


Fig. 2. Layout of fluid handling system and position of pH sensor.

Once the fabric strip was connected to the channel, the system was left for 50 minutes. The change in mass of the channel and absorbent was recorded with time. The results are shown in Fig. 3. The initial five minutes represent the time it takes for the liquid to travel across the fabric strip and reach

the fluidic channel. Following this, there appears to be a continuous increase in mass with time.

Using this data, the flow rate of the liquid through the fluidic channel can be measured. The results are shown in Fig. 4. It can be seen that once the system has stabilized the average flow rate is 11 mg/min.

The change in weight of the absorbent was measured to be 274.1 g. It was observed during the trial that it took 21 minutes for the liquid to reach the absorbent. Therefore the rate of flow of the liquid into the pump can be calculated to be approximately 9 mg/min. The fluidic channel was also weighed before and after the trial and found to increase by 72 g. This accounts for the difference in flow rate measured using the balance and by weighing the absorbent before and after the trial.

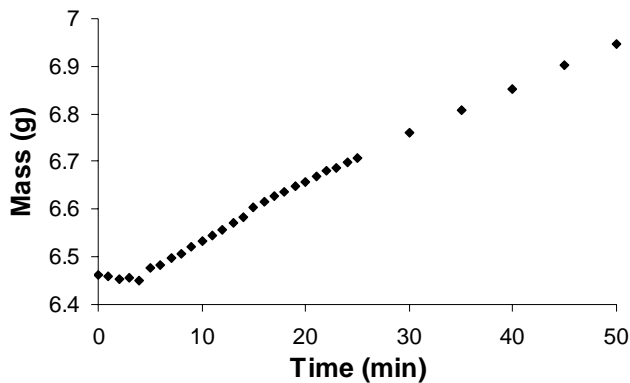


Fig. 3. Change in mass of the fluidic channel and absorbent with time.

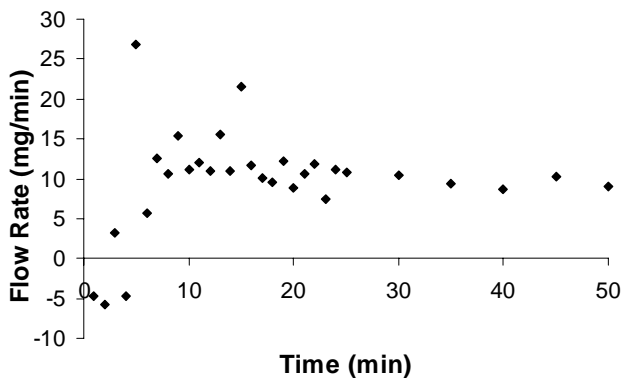


Fig. 4. Change in flow rate through the fluidic channel with time.

The values measured above are similar to the sweat rate measured by Patterson et al for the lower back, as  $0.85 \pm 0.41 \text{ mg cm}^{-2} \text{ min}^{-1}$  corresponds to flow rates between 9 and 28 mg/min over the area covered by the fabric patch [10]. However, it is important to state that it is not only the dimensions of the channel which influence the flow rate. Once contact is made with the absorbent, it can act to draw liquid through the channel. The effect of the absorbent can clearly be seen in Fig. 5, where the experimental set-up shown in Fig. 2 is used for fluidic channels, which both have acquisition layers. The first is tested without an absorbent and the second

is tested with it. The weight gain for the channel without an absorbent is due to the fluid collected by the acquisition layer.

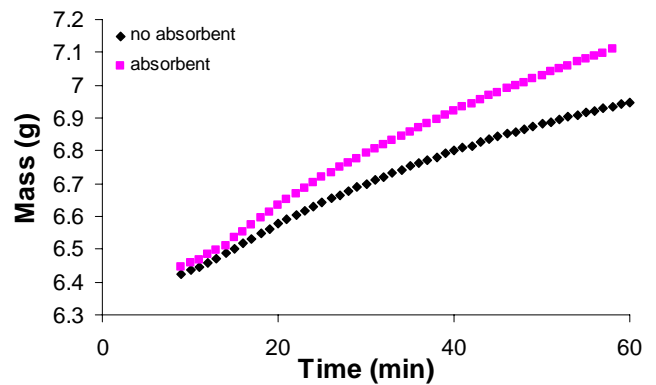


Fig. 5. Effect of absorbent on flow rate through fluidic channel.

It can be seen that the fluidic channel is capable of transporting liquids at a controlled speed and definite direction. Furthermore, the major factors influencing the flow rate are channel dimensions and the presence of the absorbent.

### B. In-vivo testing

For on-body trials the fabric patch was placed in a narrow belt with a transparent cover. The belt was positioned on the subjects back as shown in Fig. 6.

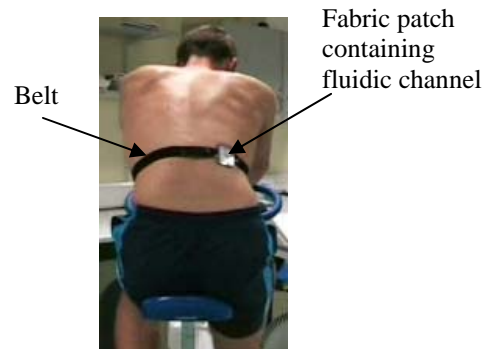


Fig. 6. Effect of absorbent on flow rate through fluidic channel.

To verify sweat collection, movement of fluid along the channel, and delivery to the absorbent, a green food dye was placed at the inlet, as shown in Fig. 7. The subject was then asked to cycle for 25 minutes. During this time, the sweat gathered by the system moves the food dye along the fluidic channel and into the absorbent.

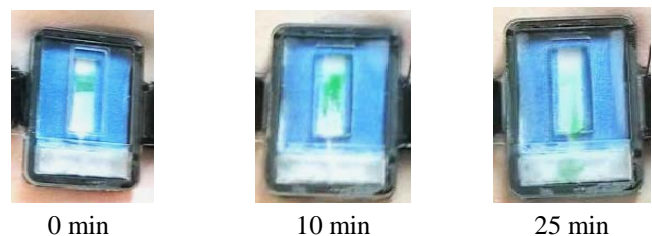


Fig. 7. Movement of food dye through fluidic channel.

To determine flow rate the acquisition layer, supplied by Smartex ([www.smartex.ie](http://www.smartex.ie)), was placed at the back of the

fabric patch to ensure complete collection of sweat over the area of interest. A pH sensitive dye was also placed on the fluidic channel. The dye changes colour depending on the nature (acidic or basic) of the sweat and is used to easily identify the presence of liquid along the fluidic channel.

For in-vivo experiments, the subject was asked to cycle for 40 minutes. During this time, the colour of the pH sensitive dye was recorded. Furthermore, the weight of the absorbent, fluidic platform and acquisition layer was measured before and after the trial in order to obtain an approximate value of the flow rate.

The change in colour of the pH sensitive dye is shown in Fig. 8. It can be seen that it takes 32 minutes for a complete colour change to occur. This is reasonable considering it takes a normal person approximately 10 – 15 minutes to start sweating in appreciable quantities. Following this, a further 10 minutes is required to soak the acquisition layer with sweat and for this to move towards the inlet at the back of the fabric patch and enter the fluidic channel.

Table 1 shows the change in mass of the fluidic platform, acquisition layer and absorbent before and after the trial. From the increase in mass of the absorbent the flow rate is estimated to be 16 mg/min, which is considered typical of the flow rate measured for adult males in the lower back.



Fig. 8. Change in colour of pH sensitive dye during exercise trial.

TABLE I  
MASS OF FLUIDIC PLATFORM, ACQUISITION LAYER AND ABSORBENT BEFORE AND AFTER EXERCISE TRIAL

Component	Before (g)	After (g)	Difference (g)
Fluidic Platform	5.9027	6.0432	0.1405
Acquisition Layer	0.6801	1.3589	0.6788
Absorbent	0.1225	0.508	0.3855

The results clearly shown the potential of the fluidic platform to collect sweat during exercise and transport it through a pre-defined channel. This platform can be used for the analysis of sweat by placing a number of sensors along the channel. In this work, we have focused on the integration of pH, sodium and conductivity sensors. The pH sensor was developed in-house. The sodium and conductivity sensors were supplied by CEA-Leti ([www.leti.fr](http://www.leti.fr)) and the University of Pisa respectively.

### III. PH SENSOR

As stated previously, the basis of the pH sensor is a dye which changes colour depending on the acidic or basic nature of the sweat moving through the fluidic channel. During exercise, human sweat typically varies from pH 5 – 7 and is largely dependent on sweat rate [11]. In addition, the sweat acid-base character has been shown to relate to sodium and chloride ion concentrations making pH a useful parameter to measure in parallel with electrolyte levels [10].

Bromocresol purple (BCP,  $pK_a = 6.2$ ) is suitable for the required range of measurement and is fabricated directly onto the fabric channel by co-immobilising the dye with tetraoctyl ammonium bromide.

A black PMMA cover, prepared in-house, holds the paired emitter-detector LED configuration used to make quantitative measurements [12]. The Red LED's (Kingbright, L934sRCG) are used to detect absorbance as the dye changes from yellow to blue, depending on pH. The sensor and optical system is illustrated in Fig. 9.

The LEDs are controlled and monitored by a Mica2dot mote. The detector LED is reverse biased at a specific voltage to generate photocurrent upon incident light. This photocurrent then discharges the LED at a rate that is proportional to the intensity of light that is reaching the detector. A simple threshold detection/timer routine is implemented and data is transmitted to a Mica2 base station connected to a laptop for analysis.

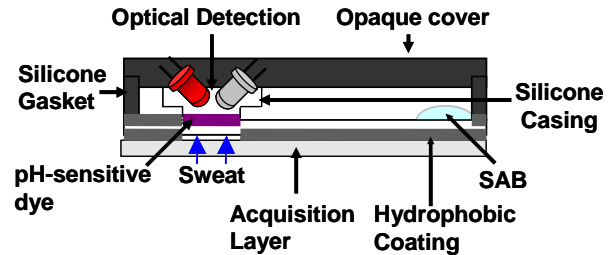


Fig. 9. Illustration of pH sensor and optical detection system

The system has been calibrated using artificial sweat with pH values ranging from 4 to 8 in steps of 0.2 pH. The results are shown in Fig. 10. It can be seen that the response of the dye is repeatable over the range of interest.

A waistband has been fabricated by Smartex for use in on-body trials. It houses the pH sensor, sensor electronics and reference patch. An image of the waistband placed on a subject during trials is shown in Fig. 11.

The pH sensor is completely enclosed by the waistband, while there is an opening to the reference patch. This is done to allow the skincheck1™ ([www.hannainst.co.uk](http://www.hannainst.co.uk)) on-skin pH meter access to the fabric. Measurements are made with this pH meter at 5 minute intervals during the exercise trial and compared to the values measured by the developed pH sensor, in order to validate the results.

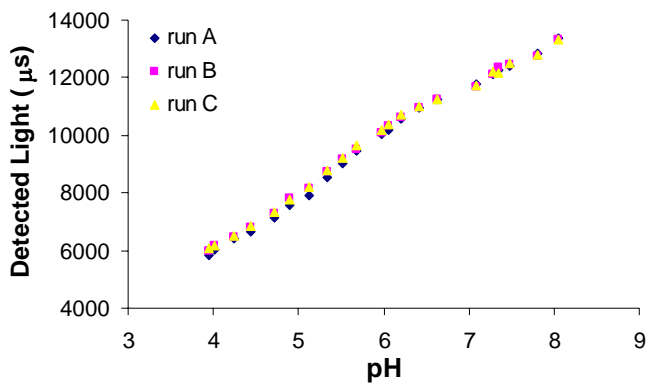


Fig. 10. Calibration curve for pH sensors

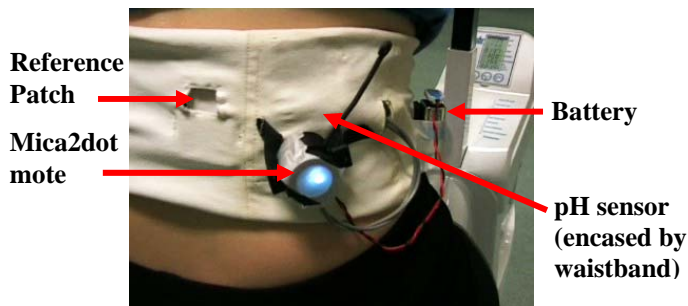


Fig. 11. Arrangement of sensor and reference patch in waistband

The pH sensor has been tested in on-body trials and an example of the results obtained is shown in Fig. 12. It can be seen that the pH of sweat increases over the time of the trial. This behaviour is also observed in the reference measurements.

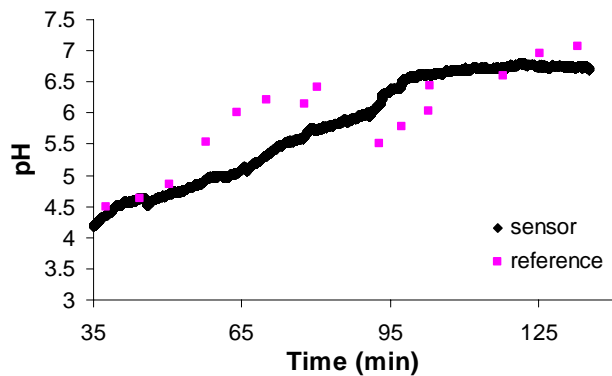


Fig. 12. Results obtained from pH sensor during in-vitro exercise trial.

Sweat is a clear hypotonic, odourless fluid containing sodium, chloride, potassium, urea, lactate, bicarbonate, calcium, ammonia, organic and non-organic compounds [13]. When measured on the skin surface it is acidic due to re-absorption processes which occur in the duct. However, when the subject starts 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 as a result. This may account for the results shown in Fig. 12.

#### IV. SODIUM AND CONDUCTIVITY SENSORS

The sodium sensor, developed by CEA-Leti, is fabricated on a flexible kapton surface and consists of a gold reference electrode and a solid contact ion selective electrode (SC-ISE). This is formed from a gold layer covered with a polymeric membrane, the potential of which is a function of the sodium concentration. In this case the polymer used is polypyrrole.

The conductivity sensor has been developed by the University of Pisa and is also fabricated on the kapton surface. The electrical conductance of sweat is a function of variables such as the species and concentrations of ions present, temperature and geometry of the conductivity cell. When the latter two are held constant it is possible to obtain a global picture of the type and concentration of ions present. An image of the pH, sodium and conductivity sensors on the caption patch is shown in Fig. 13.

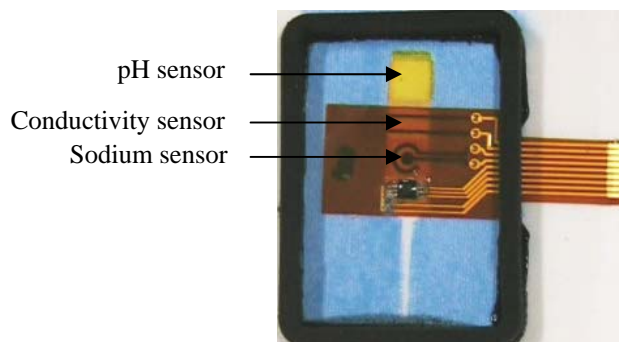


Fig. 13. Image of pH, conductivity and sodium sensors on fluidic platform

For the sodium and conductivity sensor real-time changes are recorded using control system developed by CSEM (www.csem.ch). The device has specifically been designed to interface with all the sensors developed as part of the BIOTEX project. It contains a graphical touch screen display, a removable memory-stick to simplify data storage and transfer and bluetooth communication for short-range data streaming or data download. An image of the integrated system is shown in Fig. 14.

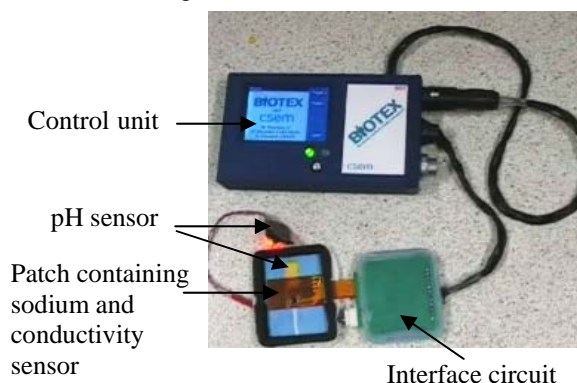


Fig. 14. pH, conductivity and sodium sensor integrated with CSEM electronics

## V. CONCLUSIONS

An initial calibration of the sodium and conductivity sensor was carried out using solutions of 0.02, 0.04, 0.06, 0.08 and 0.1 M  $\text{Na}^+$ . These were pumped through the fluidic channel at a rate of  $17 \mu\text{L}/\text{min}$ . The results are shown in Fig. 15 and Fig. 16 for sodium and conductivity sensors respectively.

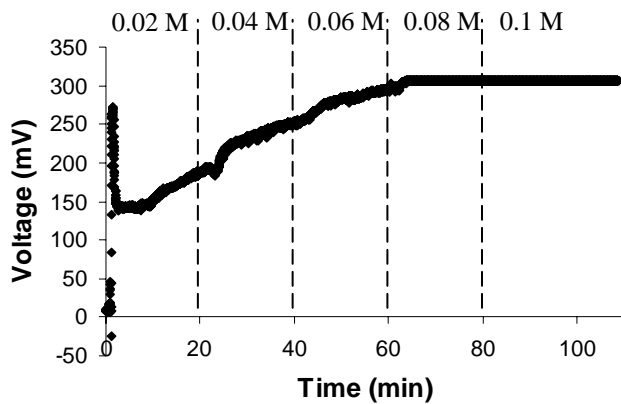


Fig. 15. Calibration curve for sodium sensor.

It can be seen from Fig. 15 that the voltage of the sodium sensor increased beyond the range which can be measured using the electronic circuit. This may require some redesign of the system.

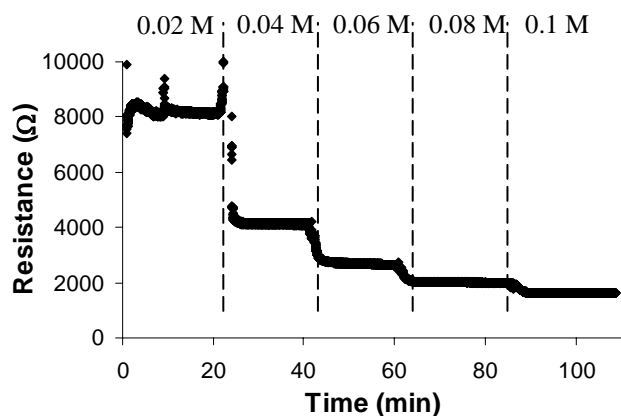


Fig. 16. Calibration curve for conductivity sensor.

In the case of the conductivity sensor (Fig. 16), a clearly defined difference can be observed for each solution. In the future, the repeatability of this sensor will be assessed. The pH sensor will also be integrated with the CSEM electronics.

It is hoped that future work will focus on the organization of on-body trials to assess the performance of the sodium and conductivity sensor. Following this, the system will be tested on normal subjects, athletes and groups such as CF sufferers. The latter group is of particular interest as the composition of their sweat is different to that of normal subjects.

In this work, the design and testing of a textile based fluid handling system has been outlined. In-vitro and in-vivo trials have shown that the system can collect and transport sweat through a pre-defined channel. It has also been demonstrated that this system provides a platform for the development of wearable biochemical sensors. The details of three sensors, developed to measure pH, sodium and conductivity have been given. Initial tests have shown that the pH sensor is capable of detecting changes in sweat composition during exercise. Initial results obtained for the sodium and conductivity sensor have shown their potential for integration into this wearable monitoring system.

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