

Bio-sensing textile based patch with integrated optical detection system for sweat monitoring

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Abstract

Sensors, which can be integrated into clothing and used to measure biochemical changes in body fluids, such as sweat, constitute a major advancement in the area of wearable sensors. Initial applications for such technology exist in personal health and sports performance monitoring. However, sample collection is a complicated matter as analysis must be done in real-time in order to obtain a useful examination of its composition. This work outlines the development of a textile-based fluid handling platform which uses a passive pump to gather sweat and move it through a pre-defined channel for analysis. The system is tested both in vitro and in vivo. In addition, a pH sensor, which depends on the use of a pH sensitive dye and paired emitter-detector LEDs to measure colour changes, has been developed. In vitro and on-body trials have shown that the sensor has the potential to record real-time variations in sweat during exercise.

1. Introduction

The use of wearable sensors to monitor various health related biometric parameters during daily activities has attracted increasing interest recently. Many people are familiar with the use of devices such as wearable heart rate monitors and pedometers for medical reasons or as part of a fitness regime. Interest in the use of such wearable systems for personal health and rehabilitation has grown as part of a wider initiative to increase the input of the individual or patient in their own care [1]. It is thought that this may assist in reducing the strain put on healthcare systems by ageing populations, rising costs and an increase in the incidence of chronic diseases requiring long term care. To date the focus has been on the use of wearable sensors to convert physical biometrics such as heart or respiration rate into electrical signals. For example, EU funded projects such as WEALTHY and MyHeart use sensorised cotton/lycra shirts to measure respiratory activity, electrocardiogram (ECG), electromyogram (EMG) and body posture [2–4]. In addition, NASA are developing a wearable patch to monitor heart rate, blood pressure and other physiological parameters [5]. Other systems include the Lifeshirt®, developed by Vivometrics®, the body monitoring system developed by BodyMedia® and the Nike-Apple iPod Sports kit [6]. Despite the growing success of sensors which monitor physical properties, relatively little has been done in the area of wearable chemical sensors which can be used for the real-time ambulatory monitoring of bodily fluids such as tears, sweat, urine and blood. Despite some successes, such as the development of the Glucowatch® and other wearable systems for monitoring sugar levels in diabetics, the widespread use of chemical sensors has been complicated by several factors which are difficult to overcome. These include sample generation, collection and delivery, sensor calibration, wearability and safety issues [6]. It is estimated that 70% of all illnesses are preventable resulting in increased costs for treatments and medication [7]. Many of these illnesses could be prevented by adopting suitable diet and partaking in regular exercise. Exercise generates sweat naturally, and sweat contains very rich information about the physiological condition of the subject as it contains a matrix of essential ions and molecules. Sweat analysis is known to be used to identify pathological disorders such as cystic fibrosis, which implies its potential as an important diagnostic tool for other disorders when suitable markers are identified [8,9]. On the other hand, real-time sweat analysis during exercise can give valuable information on dehydration and changes in the amount of important biomolecules and ions. This information is very important for monitoring the subject's physiological conditions during training/exercise and can be used to determine suitable approaches to rehydration and re-mineralisation. In the case of elite athletes and people who enjoy endurance sports, it is well known that sweat composition changes during exercise as a result of dehydration. A 2% drop in body mass due to fluid loss can have a serious effect on performance and further losses may lead to symptoms such as irritability, headache, dizziness, cramps, vomiting, increased body temperature and heart rate, increased perceived work rate, reduced mental function, slower gastric emptying [10]. Alternatively, drinking too much can lead to hyponatremia or low levels of sodium. This results in headache, nausea, muscle cramp and vomiting. If the onset of this condition occurs over a short period of time, for example during exercise, it can lead to more severe complications such as seizures, coma, brain damage and death [11]. Therefore, constant monitoring of the composition of sweat can lead to tailored rehydration strategies which improve performance and preserve the health of the athlete.

2. Physiology of sweat

There are two main types of sweat gland, apocrine and eccrine. Apocrine glands are the largest and occur in the axillae, areola of nipple and genital areas and they produce a viscous sweat containing lipids, cholesterol and steroids [12,13]. Eccrine glands cover almost the entire body and amount to between 2 and 4 million glands in adult skin. However, only 5% of these are active at any one time [14]. They have a tubular structure with a deep sub-dermal coiled secretory section which is connected to a duct which passes through the skin [15]. The primary function of eccrine sweat glands is thermoregulation with normal rate of secretion ranging from 0.5 to 1mL/min. Sweat is a clear hypotonic, odourless fluid containing sodium, chloride, potassium, urea, lactate, bicarbonate, calcium, ammonia, organic and non-organic compounds [16]. The acidic nature of the excreted sweat is most likely due to transport and re-absorption processes, which occur in the duct and are dependant on the physiological condition [17]. For example, work by Patterson et al. has showed that inducing metabolic alkalosis through the ingestion of sodium bicarbonate lead to increased blood and sweat pH. It is thought that this is due to reduced sweat acidification in the reabsorbative duct of the sweat glands. Furthermore, sweat pH will rise in response to an increased sweat rate [9,15]. A relationship has also been observed between pH and sodium (Na^+) levels in isolated sweat glands. The greater the concentration of Na^+ , the higher the sweat pH will be [18]. As exercising in a dehydrated condition has been shown to lead to increased levels of Na^+ , it can be seen that such changes can be measured directly or by monitoring sweat pH [19]. It is known that heat, mental stimuli, muscular exercise and carbon dioxide will induce active sweating in human beings [20,21]. Sweating continues as long as the stimulation lasts and subsides quickly after it ends. Thermal sweating helps maintain a constant body temperature. It occurs over the whole body surface and is centrally regulated by the hypothalamus.

3. Sweat collection and analysis

At present, sweat analysis is used in the diagnosis of disease, detection of drug abuse, as a method of testing deodorants and in optimising the performance of athletes by studying the effects of dehydration. A number of different methods are available for

sweat collection and testing. The miners method involves using a solution of iodine, castor oil and diluted alcohol painted uniformly on the skin. Once dry, a powder is placed over it so that the skin is white. Any sweat then appears as dark spots on a white background. The original method for testing the components of sweat after exercise was to use the whole bodywash down technique. The procedure involves weighing the subject before and after exercise to determine whole body sweat loss. All fluids lost during the workout are stored for analysis [18]. The method has been found to generate results with a high coefficient of variation, which has led to the development of sweat collection patches or capsules [22]. For example, a disposable sweat collector developed by Brisson et al. consisted of capsule, created inside a flexible adhesive membrane pasted onto the skin [23]. These collected samples are then stored at low temperatures for later analysis in a laboratory. At present, the pH of sweat can only be analysed when the subject has finished exercise and does not give any information on changes which might occur between the beginning and end of an exercise session. It can be seen that a real-time, wearable method of gathering and analysing sweat is in demand. This paper details the development of a textile based fluid handling system for real-timemonitoring of sweat pH. Sweat has been chosen as it is an easily accessible fluid sample. The anticipated applications of this system are in personal health and sports performance and training.

4. Experimental

4.1. Fluid handling platform

The design of the sweat collecting fluid handling platform is based on using fabrics with inherent moisture wicking properties. It collects the sweat from the skin surface and wicks the sample through a predefined channel to the sensing area. It was determined that sports materials, which are used to move sweat from the wearer's skin to the surface of the fabric where it can evaporate are ideal candidates for this application. Such material can be purchased in specialist sports stores and are generally composed of a polyester/lycra® blend. In optimising the design for the pump, a number of different channel widths and lengths were used. The performance of each design, with particular reference to positioning of sensors and flow rates, was evaluated using the experimental setup shown in Fig. 1. In this arrangement, the channel of the fabric pump is connected to a reservoir of deionised water and the weight gain of the patch and absorbent is recorded in order to calculate the flow rate. The channel dimensions were defined by coating the fabric with a silicone sealant (RS 494-118), supplied by Radionics. The final design, shown in Fig. 2, has a patch of dimensions of 55mm×40mm and a fluidic channel, measuring 7mm×20mm at the inlet and 2mm×20mm at its end. Following this a polyurethane film is affixed to the back or skin-side of the patch, leaving a window measuring 7mm×8mm as the inlet through which sweat enters the channel. An extra fluid collection layer was then attached at the back of the patch. The pH sensor is fabricated at the inlet as shown in Fig. 2. To maintain continuous fluid flow a super absorbent material was attached at the end of the fluidic channel. The absorbent (Absorbtex) supplied by Smartex (www.smartex.ie) is used. It consists of absorbing particles sandwiched between two sheets of absorbing paper and has a free swell capacity of 25 g/g and a weight of 172 g/m². Based on the average sweat rate of 17 mg/min for male athletes, approximately 5cm² of the absorbtex material is required for 2 h of continuous operation.

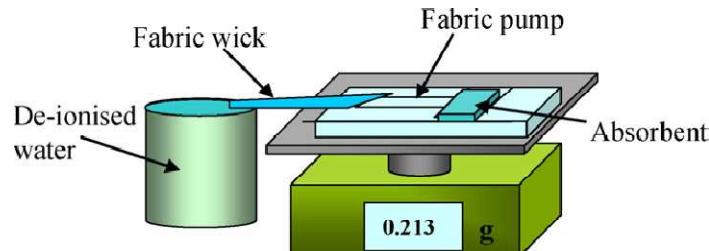


Fig. 1. Experimental arrangement for testing pump operation.

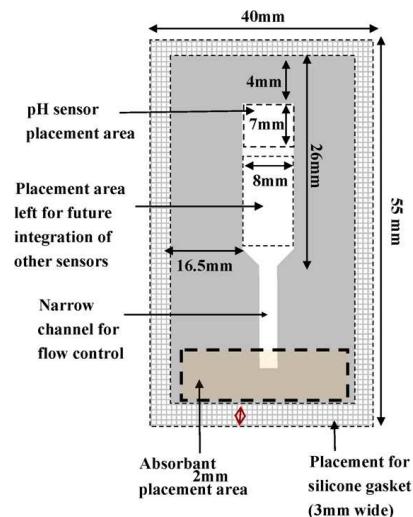


Fig. 2. Layout of fluid handling system and position of pH sensor.

Finally, a homemade black silicon rubber gasket is fixed around the fabric patch. This is used to secure the specifically machined opaque cover on which the optical detection components are mounted. It also serves to block any ambient light.

4.2. pH sensor and optical detector

A colorimetric approach was used for sweat pH measurement. This involved using a pH sensitive dye which changes colour depending on the pH of the sweat. This colour change was detected by diffuse reflectance measurement using an emitter-detector LED technique developed in our laboratory [26]. During exercise, human sweat typically varies from pH 5–7 [15]. 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. To obtain quantitative pH measurements a paired emitter-detector dual LED configuration was used. The detector LED is reverse biased at a specific voltage. The photocurrent generated upon incident light then discharges the LED at a rate that is proportional to the intensity of light reaching the detector [24]. The optical detector was controlled using a Crossbow Mica2dot mote. A simple threshold detection/timer routine is implemented and data is transmitted wirelessly to a Mica2 base station connected to a laptop for analysis. This configuration is described in detail previously [25]. Red LEDs (Kingbright, L934sRCG) with maximum emission wavelength at 610 nm were used to configure the optical sensor. The LEDs were positioned over the fabric channel fixed inside a black PMMA cover which was fitted into the rubber gasket. The sensor and optical system is illustrated in Fig. 3. For on-body trials, a waistband, fabricated by Smartex, was used. This houses the pH sensor, electronics and a reference patch. The pH sensor is enclosed by the waistband so that only the collection layer was in contact with the skin. In the case of the reference patch, there is an opening to the skin. This is done so that reference pH measurements can be made using an on-skin skincheck™ pH probe.

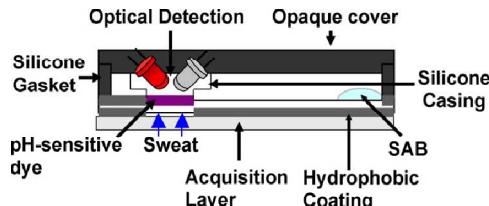


Fig. 3. Illustration of pH sensor and optical detection system.

5. Results

5.1. Fluid handling system

In this work, a fluid handling system has been developed which will allow for real-time analysis of sweat composition. Generally speaking, the development of a fluid handling system requires some method of gathering and moving fluid through the measurement system. This is generally achieved by using a micropump. Mechanical micropumps have many limitations that include high operation voltage, high power consumption, complicated configuration and incompatibility with the wearable format [26]. Therefore, this work has focused on the development of a textile based sample collection and delivery method. The basis of the textile fluidic platform is a moisture wicking material. The requirements for this material are that it has good sweat transportation efficiency, inert to sweat components, does not interfere with the sensor and be lightweight. Based on these considerations, three different polyester/lycra® blends were evaluated in terms of their fluid transportation capability, in centimetres per minute, through the warp and weft weaves. The composition of each blend and the results are shown in Table 1 where it can be seen that a density of 115 g/m² and blend of 92% polyester and 8% lycra® gave the best result and was selected for this work. The channel size (width and length) have been designed and optimised to satisfy the flow rate requirement and the number of sensors anticipated to be included in the sensing device. The rate of fluid collection by the passive pump with a channel size of 1 cm width×4 cm length is shown in Fig. 4. Three regions can be observed. These are (1) from a dry state, the rate of fluid transport through the fabric was low and was due to natural wicking by the fabric, (2) when the fluid reaches the super absorbent, the fluid movement was controlled by the absorbent and the rate of flow increased and (3) when the absorbent became saturated the rate of fluid movement slowed considerably. It was found that the rate of liquid delivery by the passive pump could be manipulated by changing the channel size and the contact area between the super absorbent and the channel. A more structured design with channel widths, 5mm, 7.5mm and 10mm, and channel lengths, 10mm, 20mm and 40mm was tested. The measured flow rate for each configuration is shown in Table 2. It can clearly be seen that the flow rate is reduced by both longer and narrower channels. In addition to allowing enough area for the sensors, the flow rate should match the rate at which the subject is expected to produce sweat during exercise. In a study by Patterson et al. on regional sweat rates in human males it was shown that there was a definite variation between the sites at which sweat rate was measured [18]. It was decided to locate the platform at the lower back where the sweat rate is approximately 0.85mg/cm⁻¹ min⁻¹. This sweat rate corresponds to a flow rate through the fluidic channel of approximately 20mg/min for the area covered by the fabric patch. This should provide a sufficient amount of sweat for analysis by the developed system. In addition, the selected location allows sensors to be integrated into a waistband to reduce artefacts from body motion. To prevent the channel being dried-out during analysis, it was tapered at its end. The effect of tapering on a fluidic channel of width 1 cm and 8mm can be seen in Table 3, where the flow rate is reduced significantly. The optimised pump design is shown in Fig. 1. A typical pump performance is shown in Fig. 5. The initial five minutes represent the time it takes for the liquid to move across the fabric strip and enter the fluidic channel. Following this, there was a continuous linear increase in the mass of the liquid uptake with time. From this data, the flow rate of the deionised water through the channel was calculated. Once the system stabilized the average flow rate was 11 mg/min. This is slightly lower than the optimal measured sweat rate for human males. However, it is envisaged that this may be useful in ensuring a stable film of sweat forms along the fluidic channel, which is essential for the correct operation of any sensor placed along it.

Table 1

Textile composition and fluid transport characteristics.

Composition	Results	
	Warp	Weft
65 g/m ² polyester 75% lycra 25%	6.4 cm/5 min	3.7 cm/5 min
210 g/m ² polyester 92% lycra 8%	4.9 cm/5 min	7.3 cm/5 min
115 g/m ² polyester 92% lycra 8%	8.8 cm/5 min	8.2 cm/5 min

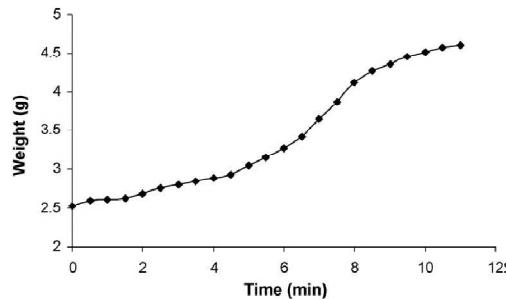


Fig. 4. Passive pumping mechanism on fluid handling system.

Table 2

Influence of channel width and length on flow rate.

Channel length	Flow rate		
	Channel width=5mm	Channel width = 7.5mm	Channel width = 7.5mm
10mm	1.14 g/min	4.76 g/min	5.77 g/min
20mm	1.03 g/min	2.65 g/min	4.80 g/min
40mm	1.00 g/min	1.25 g/min	2.60 g/min

Table 3

Effect of tapering on flow rate for channels of width 1 cm and 8mm.

Channel dimensions	Flow rate
1 cm-channel	2600 mg/min
1 cm-tapered channel	1000 mg/min
8mm-channel	1250 mg/min
8mm-channel tapered	500mg/min

Fig. 5. Mass of fluid absorbed.

5.2. pH sensor

5.2.1. On-fabric pH sensor

A number of methods currently exist for the measurement of pH. The most popular of these is the pH-probe, which can be placed in contact with the skin in order to measure pH. The drawback to this approach is that the probe cannot be held in-contact with the skin over a long period of time and it would be prone to drift and motion artefacts. An ideal wearable sweat pH sensor would be to use the textile itself as the sensor where sweat is collected and moves away continuously, hence providing fresh sample for analysis at all times. This concept is investigated by immobilising a pH sensitive reagent directly onto a textile material which will give a visible colour change with variation of sweat pH. An optical detector can then be used to obtain a quantitative measure of these colour changes. In this work a 5-L drop BCP dye was immobilised onto the polyester/lycra® blend using a stamp and left to dry for at least 1 h. The response of the on-fabric pH sensor was evaluated in by calibration with buffer solutions. The results are shown in Fig. 6. The sensor exhibited a colour change from yellow to blue in the region pH 4–7 which was detected by the optical detector. The detected light intensity is plotted against the pH value in Fig. 7. The model for the best-fit sigmoid curve fitted to the data was

$$I = (a/(1 + e^{b(pH-z)})) + c$$

where I is the detected light intensity, a is the peak height, b is the slope coefficient, z is the point of inflection and c accounts for a baseline offset [26]. The pK_a for this sensor is estimated to be 6.5 which is slightly higher than the literature value of 6.2. However, it has been shown that immobilization would increase this value due to a change of microenvironment [27]. The stability of the textile based colorimetric sensor was demonstrated by repetitive calibrations that showed good repeatability with relative standard deviation (R.S.D.) typically within 2% (see Fig. 7). This indicated that the pH indicator dye was fully reversible to pH changes to allow repeated calibrations and that no significant dye leaching occurred during the experiments. We therefore believe that the performance of the proposed sweat pH sensor to be able to satisfy the realtime on-body measurement during the envisaged application that involves a single 2-h physical exercise session. At present, the sensor fabrication is done manually so that it is not possible to control sensor membrane thickness. Therefore, individual sensors have to be calibrated with 2 pH buffer solutions after each trial. This may not be necessary in the future as we are looking at the possibility of inkjet printing which can give much more accurate dye loading; therefore more consistent responses between sensors are expected.

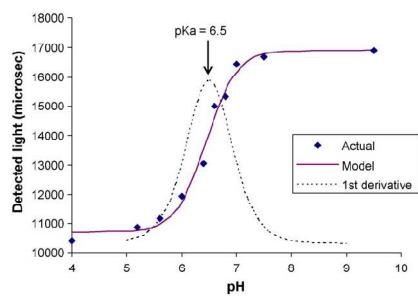


Fig. 6. Calibration curve showing pH vs. detected light.

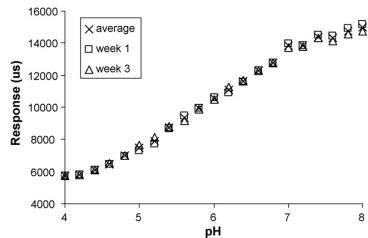


Fig. 7. Repeat calibration of a textile based pH sensor to demonstrate the stability and repeatability of the sensor.

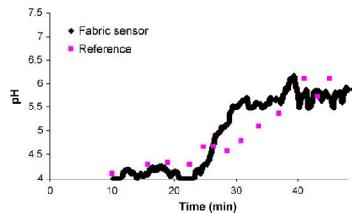


Fig. 8. pH values recorded during on-body trial.

5.2.2. On-body trials

Sweat rate and fluid losses vary for individuals and are generally dependent on body size, gender, exercise intensity, environmental conditions and individual metabolism [28]. In testing the developed patch on body, it has been observed that it takes approximately 10–15min to produce an appreciable amount of sweat during exercise. Following this, a further 5–10min must be allowed for the acquisition layer to become saturated for sufficient sweat to enter the channel of the fluid handling system. In general the priming process takes from 25 to 30min. For on-body trials, the subject was equipped with a waistband containing the fluidic platform with pH sensor and a reference patch. After 10min of cycling, continuous pH measurements were initiated. Reference measurements were taken manually at fixed time intervals. Many on-body trials were conducted and in Fig. 8 is a typical real-time response profile that shows that the sweat pH analyser compared reasonably well with the commercial pH probe. There was a significant increase in the measured pH after 25min and this represents the time when sweat rate began to increase during exercise. The increase in sweat pH with time measured corresponds well with what has been expected from the literature [9, 15]. There are some discrepancies between the values of the pH sensor and the reference measurements. It was due to a number of factors, for example, the direct contact of pH probe on the textile is likely to affect the output data. Also, the sweat sample on the reference patch were open to air and therefore had the opportunity to interact with carbon dioxide of the atmosphere, hence resulting in lower pH values. This is the major advantage of our proposed sweat pH monitoring system which measures the sweat pH from where it emerges and within an almost enclose package. Future work will focus on the integration of the pH sensor with sodium and conductivity sensors and the use of a Bluetooth communication system for sensor control. Furthermore, this work will focus on reducing the error between the calibration pH values and those measured by the sensor.

6. Conclusion

In this work, the design of a textile based fluid handling system and pH sensor based on paired emitter-detector LEDs has been outlined. The ability of the fluid handing system to collect sweat from the skin and transport it in a controlled way down the channel and into the absorbent has been demonstrated during in vitro and in vivo trials. Furthermore, it has been shown that by placing sensors along the channel, a biochemical analysis of that sweat can be obtained. The pH sensor developed in this work has shown an increase in sweat pH during exercise, which can be explained by considering the relationship between pH and sweat rate.

Acknowledgements

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