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A wearable conductivity sensor for wireless real-time sweat monitoring

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ABSTRACT

We designed, fabricated, and tested a sweat-based conductivity sensor device toward a real-time, non-invasive physiological condition monitoring device for humans. Sweat collector, conductivity sensor, and the interfacing circuit were developed and combined to form a wearable device. Polydimethylsiloxane (PDMS) based sweat collector was fabricated to collect sweat from skin using the hydraulic pumping action of sweat glands. PDMS sweat collectors were prepared using 3D printed plastic molds. The interfacing circuit was designed based on the results of the conductivity sensor that was characterized by the Electrochemical Impedance Spectroscopy. Human testing was performed to prove the feasibility of the proposed sweat sensing system for the real-time non-invasive monitoring of human sweat. The first reading from the device was obtained in 7–20 min depending on the subject and the location of the electrodes. Sweat rate plateaued after a consistent work load of exercise, as was expected. The sweat conductivity decayed after the first readings due to the initial mineral content of the skin. Finally, an increasing trend in sweat conductivity was observed which may be due to subjects' changing hydration level.

1. Introduction

As one of the most readily accessible human biofluids, sweat can be used to provide information about one's electrolyte concentrations [1,2]. Hypohydration and hyperhydration have received the greatest attention but, as Maughan and Shireffs wrote, if the desired goal is to provide individualized hydration and rehydration prescriptions it is as important to monitor the plasma osmolality [3]. The American College of Sports Medicine Position Stand on Exercise and Fluid Replacement states that, “Because there is considerable variability in sweating rates and sweat electrolyte content between individuals customized fluid replacement programs are recommended.” [4]. Sweat is hypotonic when compared to plasma but the actual composition varies as the result of many factors including sweat rate, acclimation and diet [3]. Currently, blood serum analysis is considered to be the gold standard method of electrolyte concentrations. However, this technique is highly invasive and is impractical for real-time, on-the-field assessment of hydration during competition [5,6]. Alternately, real-time sampling of sweat has become a possibility as a potential proxy measure for plasma, although further work is needed to establish validity.

Using sweat as a biomarker has recently drawn attention and several studies have been carried out to explore the potential of sweat sensing [2,7,8]. Approaches include, but are not limited to, optical detection with porous fabrics [7], attachable tattoo paper with Ion Selective Electrodes (ISEs) [9], and incorporating organic dyes [8]. Recently, Electrochemical Impedance Spectroscopy (EIS) has been successfully utilized for conductometric sensing applications [10–13]. Conductometric-based sensors offer simplicity and ease of manufacturability making the technique very popular in sensing devices such as biomedical diagnostic probes, sensors for environmental monitoring, and microfluidic biosensors [10,14,15].

Recent growth in wrist watch-based wearable devices, such as Fitbit®, G-watch, and heart-rate monitors [16–18], has led several researchers to focus on the development of a wearable device that can measure other physiologic processes during exercise [19,20].

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Previous work includes monitoring of body temperature, heart rate, accidental falls, and movement [20–22]. The idea of using wearable devices for monitoring sweat electrolyte concentration is a fairly new but emergent concept, primarily targeting collegiate and professional athletes. De Rossi and his colleagues proposed a device that measures sweat rate by integrating two humidity sensors on a textile substrate whereby differential outputs were used to calculate the sweat rate [23]. Diamond's group fabricated an optical sweat-based pH sensor by incorporating a pH sensitive dye with a micro-LED/photodetector pair [7].

A wearable device for physiological activity monitoring can be broken down into three parts; data collection, data processing, and transmission [19]. Sweat monitoring, in particular, can be detailed into the following steps: (1) collecting sweat, (2) sensing the sweat analyte, (3) circuit interface, (4) data processing, and (5) transmission.

In this paper, we present a conductivity sensor based sweat sensing system packaged as a wrist watch. The prototype collects sweat from the forearm, reads the conductivity value and transmits the data wirelessly to a smart phone via a Bluetooth® transceiver. The results show that the proposed system has a potential ground-breaking ramification as it opens the gate for assessing real-time sweat electrolyte status of athletes during practice and competition.

2. Results and discussion

2.1. Sweat collector

The human body secretes sweat through eccrine sweat glands mainly to regulate the body temperature [24]. There have been many different methods used to measure the density and distribution of eccrine sweat gland distribution in humans. Scientists have used thermal, exercise, pharmacological, electrophysiological, and pharmacological stimuli to assess sweat. No matter the methodology utilized, it is clear that there is a large distribution in eccrine sweat glands density specific to regional anatomical surface areas. For example, the volar surfaces of the hand and foot have the highest reported densities approximating greater than 500 glands/cm^2; the skin of dorsal forearm, from which we sampled, has an approximate density of 135–145 glands/cm^2 [25]. If the sweat excreted through the sweat glands to the skin pores can be directed to a collection channel, it can then be analyzed for composition. One of the established techniques is to use a Macroduct sweat collector [26]. The idea is to have a small hole on a plastic piece where sweat is guided through a plastic tube. We have used this idea to create our own design using a moldable plastic polymer called polydimethylsiloxane (PDMS) which is a biocompatible material that is used in microfluidics applications [27,28]. The elastic modulus of PDMS is close to human skin's elastic modulus, which makes PDMS more compatible and comfortable to wear on the skin. Sweat content analysis is traditionally performed by collecting sweat via whole body wash down technique [29] or using absorbent pads [30–34]. It is known that covering the sweat collection area prevents sweat from evaporating resulting in lower local sweat rates and alterations in sweat content, which is known as hydromeiosis, and can be minimized with Macroduct sweat collectors [35]. This method was the basis of our design, where a hole on the PDMS is used to guide the sweat into the sweat collection and analysis channel tubing. Although PDMS is permeable, lab on a chip applications mostly employ PDMS as the building platform as it is practically inert in terms of interactions with biological liquids and constituents [36,37]. Teflon tubing, commonly used in microfluidics devices, was used to guide the sweat as an outlet.

PDMS molds are created by mixing the curing agent with PDMS solution in a 10 to 1 ratio. The solution is mixed for 5 min. The newly formed mixture is then poured into the desired 3D mold (4 cm × 4 cm square with a height of 1 cm) that was printed using a Flashforge 3D printer and ABS as the building material and placed in the vacuum chamber. 3D molds were treated with Methyl ethyl ketone (MEK, or known as butanone) to enhance PDMS curing. PDMS curing agent contains tetramethyl tetravinyl cyclotetrasiloxane that crosslink with PDMS by radical polymerization. However, ABS contains butadiene that has C=C bonds. These bonds react with free radicals in the PDMS crosslinker and significantly reduce even prevent PDMS radical polymerization [38,39]. MEK, on the other hand, contains C=O bonds that do not react with the radicals from crosslinkers. Consequently, MEK coating prevents the cross-linkers from reacting with the butadiene, which allows the curing process to proceed. The vacuum chamber process is done until the PDMS becomes bubble free and transparent. The mold is then placed in the oven to bake at 70 °C for 2–3 h. Once baked and taken out of the oven, the solid PDMS is removed from the 3D mold.

An illustration of the sweat conductivity sensor prototype is given in Fig. 1a. A tube is inserted through a hole that is punched at the center of the PDMS mold. Sweat is collected through the hole and the tube by hydraulic pressure from sweat glands. The PDMS is in contact with the user's skin, and the pressure difference allows the sweat to travel upwards through the tube. Although capillary forces are also present in the tubing, the main force is the sweat secretion from the sweat glands, which acts as a hydraulic pump. Therefore, the increasing pressure in the tube will not have significant effect on sweating mechanisms. Moreover, the tubing is kept short (few centimeters) to just allow sweat draining. Two conductivity sensor wires were placed into the tube using a needle as a thread, from the side of the mold, with one wire above the other (as shown in Fig. 1). Due to the nature of the manual insertion, there will be slight device to device variation in terms of the locations of the wires. However, since each device is characterized and calibrated individually, this variation will not cause issues. The PDMS mold is placed into a wristband with a metal frame that is harvested from a commercial LED watch [40]. The interface circuitry (built on an in-house printed circuit board, PCB) is also placed on top of the PDMS sweat collector. A 22 gauge Teflon tubing is pushed close to the end (but not all the way) to allow sweat go through the punched hole as illustrated in Fig. 1.

The hole to the PDMS was created by a 1.2 mm puncher. The outer and inner diameters of the 22 gauge Teflon tubing were

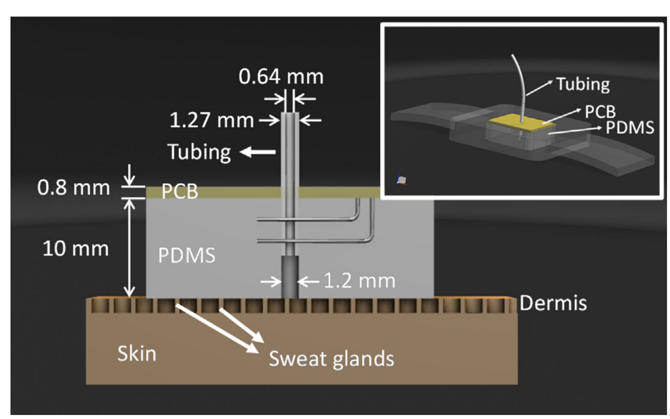

Fig. 1. 3D model of the sweat sensor prototype. Inset shows the overall design including the wrist watch metal frame and wrist band, PDMS sweat collector, and the PCB. PDMS directly touches the skin allowing sweat glands to secrete the sweat through the collection hole and the tubing. As the sweat goes through the tubing, it passes through two wires which are connected to the PCB to measure the conductivity of the sweat.