Wearable Lab on Body: Combining Sensing of Biochemical and Digital Markers in a Wearable Device

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***Abstract*— Wearables are being widely researched for monitoring individual's health and wellbeing. Current generation wearable devices sense an individual's physiological data such as heart rate, respiration, electrodermal activity, and EEG, but lack in sensing their biological counterparts, which drive the majority of individual's physiological signals. On the other hand, biosensors for detecting biochemical markers are currently limited to one-time use, are non-continuous and don't provide flexibility in choosing which biomarker they sense. We present "wearable lab on body", a platform for active continuous monitoring of human biomarkers from the biological fluid. Our platform contains both digital sensors such as IMU for activity recognition, as well as an automated system for continuous sampling of biomarkers from saliva by leveraging already existing paper-based biochemical sensors. The platform could aid with longitudinal studies of biomarkers and early diagnosis of diseases.**

I. Introduction

A. Wearable Augmentation and Digital Sensing

Wearable technology has enabled on-body real-time sensing and computing of human physiological information. Researchers have developed a variety of sensors to sense the internal (EEG, EOG, EMG, skin conductivity, heart rate, etc.) and external state (movement, location, interaction, etc.) of a person [1]. This information collected from the body can be used to provide real-time feedback and assistance to the person through multimodal actuators including audio [2], visual [3], olfactory [4], electrical [5], and haptic stimulation [6]. Thus, the wearable technology becomes a closed-loop platform for augmenting human capabilities [7].

With the advancement of radio and wireless sensing [8], researchers have also demonstrated the ability to monitor human physiological changes without placing any sensor on the human body. This kind of research is enabled by the combination of high-resolution wireless sensing technology and advanced machine learning algorithms. Researchers have demonstrated the applications of wireless sensing to detect body movement [9], breathing cycle [10], heart rate [11], emotion [12] and sleep stages [13] without any on-body monitoring devices. This digital sensing of physiological signals provides information about the higher level state of the individual rather than capturing the molecular level biological processes that drive the physiological states.

B. Biological Sensing

Beyond the digital sensing of human physiology, biochemical markers are molecules used to indicate certain biological phenomena related to behavior, disease, infection, or environmental exposure [14]. These molecular biomarkers include organic and non-organic compounds that are released or secreted as part of the human metabolism. In medicine, these biochemical markers reveal insights into human health at the molecular level, which could be used for personalized medicine that is either prognostic or predictive [15].

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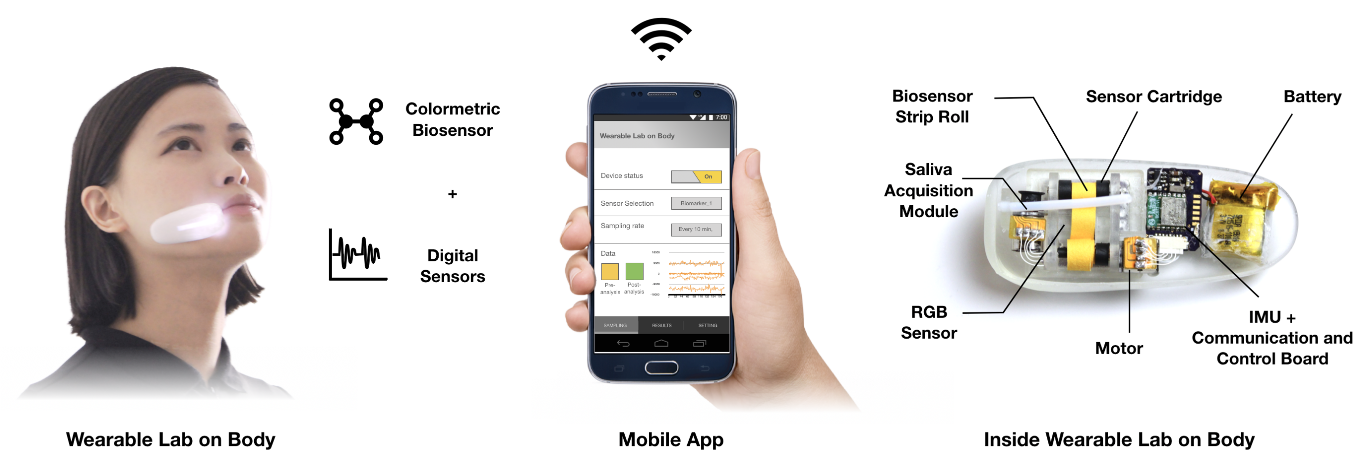

Fig. 1. The overview of the wearable lab on body platform, combining biochemical and digital sensing in a wearable device

Saliva is an emerging biological fluid for sensing of biomarkers and diagnostic [16]. Saliva is a clear, slightly acidic, complex solution, is produced about 0.75 − 1.5 L daily in the human body, and is composed of secretions from major salivary glands. Similar to blood, saliva contains various biomarkers including hormones, enzymes, antibodies, antimicrobial, and growth factors [17][18]. Many of these biochemicals enter saliva from the blood by passing through the spaces between cells. Therefore, the major compounds found in blood are also detectable in saliva. Thus saliva is functionally homologous to serum in reflecting the physiological state of the body, including emotional, hormonal, nutritional, and metabolic variations [16].

In this paper, we propose that the next generation of wearable technology must bridge the gap between digital physiological sensing and biochemical sensing to capture a holistic model of the individual's internal and external state. We present our approach by developing "wearable lab on body", a platform for a semi-invasive and minimally obtrusive biological wearable sensors that continuously monitor biomarkers from saliva. Our platform contains both digital sensors such as IMU for activity recognition, as well as biosensors for continuous monitoring of biochemical markers by leveraging already existing paper-based sensors. Our platform could aid in early diagnosis of diseases by analyzing trends of biomarkers in saliva as well as improving human health.

II. Related work

The development of biomarker sensors has evolved from an invasive to a non-invasive approach [19]. Low-cost biosensor platforms have enabled the detection of the biomarkers in body fluids by coating chemical receptors on a flexible substrate such as a paper strip or a microfluidic channel [20] [21]. The individual spits or takes a swab of their body fluid (saliva, sweat, urine, or blood), and places it on the platform. Chemical receptors on the sensor would bind and react to the biomarker molecules reporting the presence of the biomarker through a chemical reaction, such as a change in color [22], fluorescing [23], or sending out an electrochemical signal [24].

The use of colorimetric reaction is one of the key methods for reporting the presence of the markers in the paper-based sensors. Researchers have developed Dermal Abyss, a smart tattoo created with colorimetric and fluorescent biosensors that change color according to the interstitial fluid [25]. Further, researchers have used capillary flow for detection of biomarkers in saliva [23]. The concept of microfluidics on paper has been used to create Ampli [26], a plug and play set of paper-based blocks that could be arranged in various configurations for testing biochemical reactions in real-time for personalized diagnostics.

A few researchers have begun to develop wearable methods for monitoring of the molecular biomarkers [27] by integrating colorimetric sensors into the human body. For example, researchers have designed a wearable microfluidic device for capture, storage, and colorimetric sensing of glucose, chloride lactate, and pH from sweat [28]. In addition, researchers have also developed a nanoporous membrane-based wearable sensor that detects cortisol in sweat [29]. However, these wearable sensor platforms are limited to one-time use and don't provide flexibility in choosing which biomarker they sense.

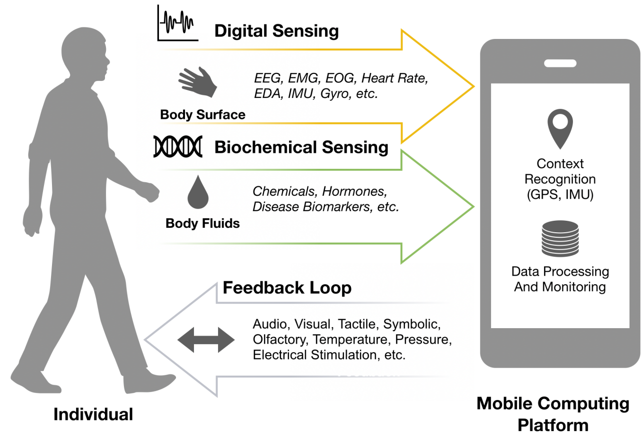

Fig. 2. Our vision for bio-digital wearable platform that bridge the gap between biochemical sensing and digital sensing

In term of saliva, paper-based sensors have been widely developed to sense multiple biomarkers such as cortisol [30], glucose [31], nitric oxide [32], pH [33],and more [34]. These biomarkers have been used to detect signs of depression [35], diabetes [36][37], heart failure [38], and periodontal diseases [39]. However, these paper-based sensors are generally limited to one-time use [40], are non-continuous and do not connect with digital platforms for data recording, analysis and building interventions.

III. Bridging the bio-digital sensing

Looking at the current literature, most of the biochemical sensing platforms lack the ability to monitor context and activity of the individual, whereas the digital sensing platforms can only sense physiological signals but are not able to sense the molecular dynamics of the human body. Here, we present a vision for the future bio-digital wearable device that bridges the gap between biochemical sensing and digital sensing. Our approach consists of four modules: biochemical sensors, digital sensors, mobile computing module, and feedback modality as illustrated in Fig. 2.

The main advantage of such a bio-digital wearable platform is that it enables the continuous monitoring of behavior and wellbeing of the individual in real-world settings. Using digital sensors such as IMU and GPS, the system can recognize the context of the individual regarding location and activity, while physiological sensing such as EEG could help the system to recognize the cognitive performance of the individual in terms of attention and emotion. The biological sensors could help quantify the molecular response of the body, for example by measuring changes in cortisol for stress. The information from both the biochemical and digital

Fig. 3. The position of the wearable lab on a user

sensors can contextualize one another, and provide insights on the effects of an individual's behavior, which in turn can be used to develop healthier lifestyles. With the closed loop system, the platform could also provide real-time feedback to the individual when recognizing unhealthy behavior.

IV. Implementation

To illustrate our vision, we prototyped a bio-digital platform for sensing of the body fluid, saliva. Our novel platform can 1) perform real-time continuous monitoring of biochemical markers on the body, 2) integrate plug and play paper-based flexible biosensors with digital sensors, 3) convert colorimetric information from the biochemical sensing reaction to the digital readout.

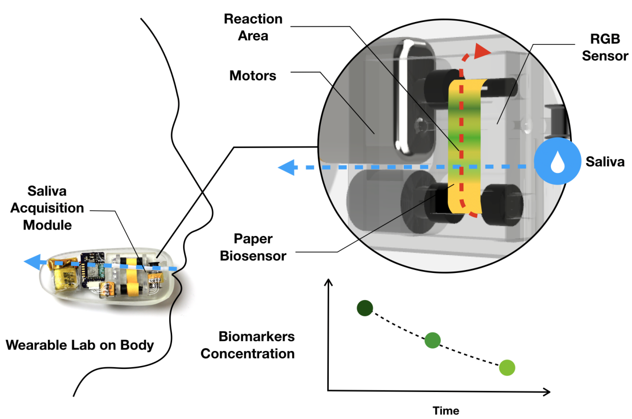

Fig. 4. The mechanical arrangement of saliva acquisition and rotating biosensor strip

Our platform is designed to continuously sample saliva from the individual and analyze it using a roll of multiplexed biochemical sensors. A small portion of the sensor is exposed to the acquired saliva at a point in time. Once the saliva reacts with a biochemical sensor, the RGB color sensor on the device reads the output and converts the value into the concentration of the biomarker based on the color-concentration model. The used sensor is then switched with a new sensor in the roll. The platform consists of three main components: a paper-based biochemical sensor cartridge, a saliva acquisition and sensing module, and a smartphone application to store and analyze the data.

A. Paper-based Biochemical Sensor Cartridge

The paper sensor cartridge is a roll of paper-based, biochemical sensors strips that can be installed in the module. The paper sensor type is dependent upon the type of biomarker the individual wants to monitor. For monitoring multiple biomarkers, multiple biochemical paper sensors could be interleaved in the cartridge. The paper sensor strips have a thin film of impermeable transparent plastic on the backside to prevent cross-contamination from already sensed or acquired saliva. The width of the paper sensor that the current version of the device supports is 5.5 mm. One can vary the number of samples collected for a specific biomarker by varying the number of paper-based sensors for that biomarker on the tape. Sample RGB profiles of the medical grade commercially available saliva pH (biomarker for periodontal disease) sensor and nitric oxide (biomarker for heart failure) sensor are shown in Fig. 5.

B. Saliva Acquisition and Sensing Module

The saliva acquisition and sensing module consist of a mechanical arrangement for acquiring a small quantity of saliva from *buccal mucosa* (inside of the cheek). It consists of two stepper motors, a small PTFE tube, a length of braided nylon cord, a paper sensor cartridge and the electronics for digital sensing. The arrangement is illustrated in Fig. 4 The PTFE tube of diameter 2mm is held against the inside part of the cheek while the rest of the device sits outside the cheek. A stepper motor is used to circulate the cord against the cheek and through the device, collecting a small amount of saliva. The gathered saliva is then transferred onto the paper sensor by contact. Another stepper motor is then used to advance the paper sensor cartridge. A new portion of the paper sensor is rolled out and swabs the saliva from the cord. This motion is repeated several times to get the appropriate amount of saliva onto the paper sensor. The synchronous motion of the paper sensor and the collection mechanism allows the saliva to be transferred from the cord to the sensor without contaminating an unused sensor.

A color RGB sensor is mounted orthogonal to the paper sensor to track the color changes. We used the TCS34725 RGB color sensor with white LED light for illumination. The system is controlled by a BLE enabled microcontroller(BC832) mounted on a PCB inside the casing. The system also has a 9-axis Inertial Measurement Unit (MPU9250) to track orientation as well as actions of the individual. The system is powered by a single cell LiPo battery of capacity 100mAH.

C. Smartphone Application

The smartphone application accompanying the device captures and processes the sensed saliva and the IMU data. It uses the wearable's IMU data to infer the individual's activities including eating, drinking, speaking or no activity. Sample signals of these activities are given in Fig. 6. Additional activities such as walking, sleeping, and running are inferred from the Smartphone's IMU sensor [41] and are also used to decorrelate it from the device's IMU sensor.

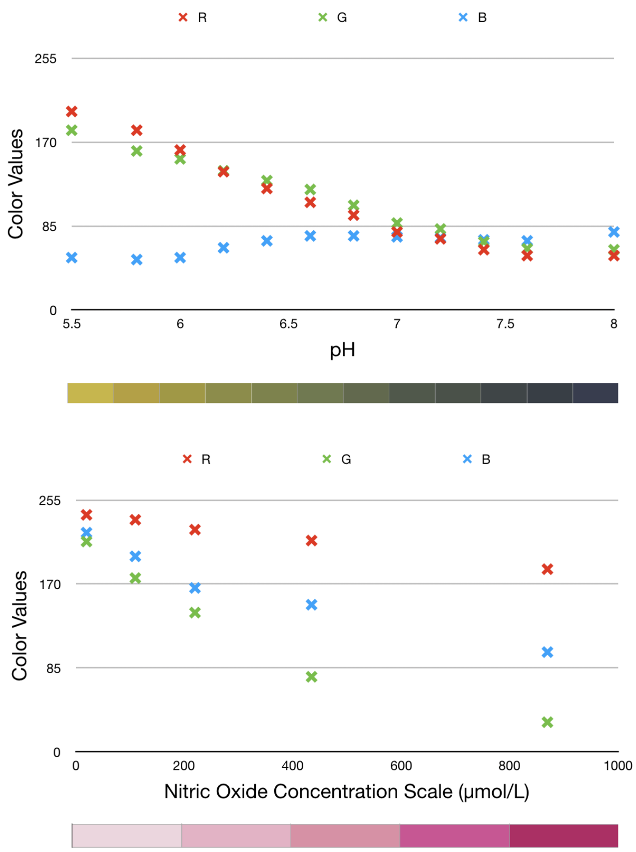

Fig. 5. The color-concentration model of pH and Nitric Oxide strips

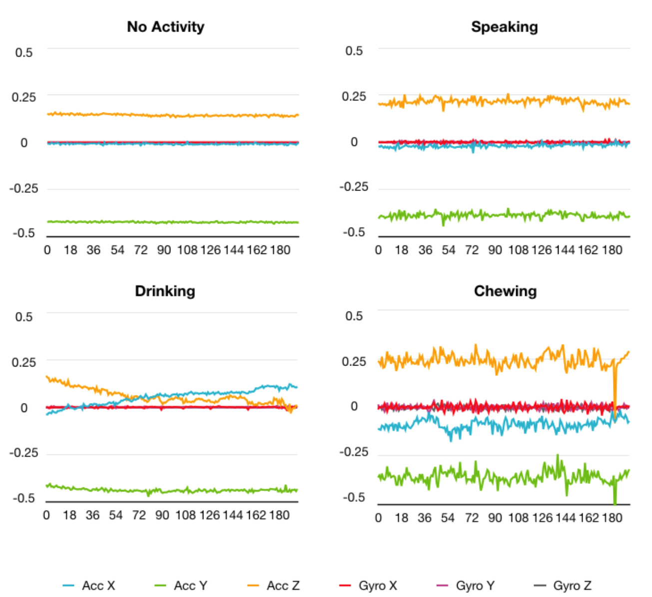

Fig. 6. Distincted IMU signals for activity recognition acquired from the user wearing the platform

Based on the context, the application models individual behavior and decides to sample the saliva after a certain time point to reduce contamination from an individual's eating or drinking. Finally, the saliva data acquired could be stored, analyzed for user feedback or sent to a physician for additional investigation or diagnosis.

V. Applications

The ability to continuously monitor saliva in a semi-invasive and minimally obtrusive wearable form factor permits diagnostics and applications that were not possible before. This section describes some possible interventions enabled by the platform.

A. Medical and Wellbeing

Previous research has shown the variability of biomarkers used for diagnosing several diseases. Variability in salivary biomarkers such as pH has been shown as an indicator of periodontal disease [39]. Different Cortisol levels have been found between morning and afternoon [42], and new biomarkers are emerging for early detection of Alzheimers [43]. Furthermore, salivary diagnostics have been found to provide a diagnosis of cancer, HIV, cardiovascular and possible neurological diseases such as Parkinsons and Huntington [44][45][46]. The ability to continuously monitor saliva would enable studying dynamic range, frequency and concentrations of biomarkers which have not been studied in longitudinal assays in humans. The method may allow to detect intricacies with the associated biomarker variations. Furthermore, the system being personal and user-specific may allow to explore the fundamental differences of biomarkers statistics between individuals. The trends found in the biomarkers could then serve for identification of disease buildup. Given the diagnosis of a disease, similar configuration of the system could also be used for scheduling optimal time and quantities of drug delivery.

B. Human-Computer Interaction

Researchers have developed various context-aware, closed-loop feedback systems which provide real-time information based on an individual's physiological signals such as heart rate, respiration, electrodermal activity, and temperature [4][47]. Several biomarkers in saliva allow for comprehensive sensing of an individual's affective state [35][48]. Our platform enables comprehensive sensing for developing closed-loop systems for mitigating pain, stress, anxiety and enhancing sleep. The biological data coupled with the digital data would allow for better modeling of the individual. Coupling other sensory modalities such as voice of the user with the biomarkers would allow for a better understanding of an individual's lifestyle and could aid in developing interventions to improve human wellbeing. This research also highlights the concept of "Biological Human-Computer Interaction " (bio HCI), a vision for the future interfaces that bridge the gap between human and computer through bio-digital system [49].

VI. Discussion and Future Work

Our platform allows for continuous sensing of an individual's biological state by leveraging already proven biochemical paper-based sensors with an individual's saliva, as well as contextual sensing through digital and mobile computing. In future work, we hope to perform user testing to determine the efficacy of the system in real time. Testing the system in a longitudinal run would allow us to see and address possible issues. We would like to incorporate a paper sensor roll only to acquire saliva samples throughout the day. As an alternative to the real-time readout of biomarkers, the roll could be sent to a lab for analysis of complex biomarkers which currently aren't available in the form of paper colorimetric analysis. We also hope to incorporate machine learning into the smartphone application for classification of individual activities. Finally, we would also like to extend the system to sense other types of biomarker sensing techniques such as electrical impedance.

VII. Conclusion

We presented a novel approach and platform for a combined bio-digital wearable device. The semi-invasive, minimally obtrusive platform allows to continuously monitor biomarkers from an individual's saliva. The platform also supports sensing the individual's biological data to infer individual body responses and digital data (IMU) to infer individual context, thereby bridging the gap between biological and digital sensors in wearable technology. This platform could be used for various applications such as early diagnostics and creating closed-loop feedback systems. We also hope that our bio-digital wearable will inspire future research in wearable biological computing for improving human health and wellbeing.

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