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Smart and Connected Bioelectronics for Seamless Health Monitoring and Persistent Human-Machine Interfaces

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Abstract

Recent advancement of flexible wearable electronics allows significant enhancement of portable, continuous health monitoring and persistent human-machine interfaces. Enabled by flexible electronic systems, smart and connected bioelectronics are accelerating the integration of innovative information science and engineering strategies, ultimately driving the rapid transformation of healthcare and medicine. Recent progress in development and engineering of soft materials has provided various opportunities to design different types of mechanically deformable systems towards smart and connected bioelectronics. Here, we summarize the key properties of soft materials and their characteristics in the context of wearable sensors and electronics. Details of functionality and sensitivity of the bioelectronics are discussed with applications in health, medicine, and machine interfaces. In addition, we introduce recent examples of bioelectronics that offer persistent human-machine interfaces to control prosthetic hands, wheelchairs, or computer interfaces.

Key words

Bioelectronics, soft materials, flexible hybrid electronics, wearable electronics, human-machine interfaces

I. Introduction

Recent advancement on the development of flexible electronics enables smart and connected bioelectronics that can be utilized in many important applications in medicine, health, and human-machine interfaces. Among those, a new electronic platform that integrates flexible materials with hard functional components is referred to as flexible hybrid electronics (FHE). In particular, advanced materials and stretchable mechanics have provided a successful integration of miniaturized chips with flexible/stretchable circuit interconnects, while maintaining small form factors. Thus, such FHE in wearable and implantable configurations can achieve a wide range of device functionalities. As an example, wearable types of FHE allow real-time, continuous, and persistent human-machine interfaces (HMI) via conformal and tissue-friendly lamination on the human skins [1-4]. In the realization of HMI, maintenance of the good skin-contact electrode that measures biopotentials is critical. However, the conventional gel electrode technique that is the gold standard for biopotential recording has limitations for prolonged, long-term use, mainly due to the electrode material (metal) and electrolyte gel. Furthermore, the conductive gel dries out and causes significant degradation of signal quality over a few hours of use. The conventional biopotential setup, even with advanced wireless technology, still incorporates bulky wires and rigid electronic systems, which hinder long-term, continuous HMI, and restricts to non-ambulatory settings.

To address these problems, a number of alternative means have been developed such as dry-contact or non-contact capacitive electrodes [5, 6]. The dry electrodes without an electrolyte gel have resolved some issues that are directly related to the gel. However, they are still problematic for long-term use due to high levels of motion artifact noise, which dramatically reduce the signal-to-noise ratio. Recent reports on capacitive, non-contact electrodes demonstrated the possibility of long-term biopotential recordings [7]. Incorporation of a soft, skin-compatible material between the electrode and the skin provided a high level of comfort. However, the bulky electronic component and inherent high impedance due to the required dielectric layer need to be further optimized for extended, everyday use.

In this paper, we summarize newly developed electrode materials to offer persistent HMI and various functional materials to design soft wearable and implantable electronics. In addition, we review a recent development of the integration of nano-microfluidic approaches with flexible electronics to offer portable health monitoring. Lastly, we discuss about the characteristics of soft-material based electronics in terms of key material compositions and device configurations. Overall, this paper delivers a comprehensive summary of soft materials, sensor integration, device design, and associated performance in the recently developed FHE.

II. Examples of Flexible Hybrid Electronics (FHE) and Persistent Human-Machine Interfaces (HMI)

1. *FHE for health monitoring*

Due to the advantages of the newly developed FHE, the next generation of disease diagnostic tools found a form of portable, point-of-care electronics. **Fig. 1** highlights several capabilities of onsite disease diagnostics, demonstrated by modern nano-microfluidic-enabled FHE devices. The device shown in **Fig. 1(a)** utilizes functionalized magnetic nanoparticles to remove a broad range of pathogens from a whole blood sample, similar to the magnetic nanoparticle-based concentration methods [8]. This methodology could reasonably be modified to target specific disease particles, enabling real-time concentration, detection, and even removal through a single device platform, which allows point-of-care disease detection. In addition to automating concentration and detection techniques, there has been a recent advancement on developing flexible, portable, fully electronic devices (**Fig. 1(b) – 1(d)**) that integrate soft materials in sensing of target molecules.

Flexibility is one of the key characteristics of non-invasive FHE enabling them to accommodate the dynamic contours of human body and for easy storage and portability. The flexible electronic device shown in **Fig. 1(b)** utilizes functionalized nanoparticles to capture human immunodeficiency virus (HIV) particles on the electronic chip. After washing and viral lysis, the integrated electrodes are used to detect a change in solution conductivity, indicating the presence of HIV. Another example in **Fig. 1(c)** shows a FHE that uses a giant magnetoresistive multilayer to detect multiple emulsion droplets that carry magnetic nanoparticles, and demonstrated full performance of sensing even with multi-modal bending situations. Similarly, the photodetector array shown in **Fig. 1(d)** is also capable of maintaining stable sensing performance under extreme mechanical bending and stretching, which shows a possible application of a hand-held diagnostic tool. These examples in **Fig. 1** account for electrical, magnetic, and light-sensitive flexible sensors, each of which will soon find important applications in integrated point-of-care devices for disease diagnostics and associated health monitoring.

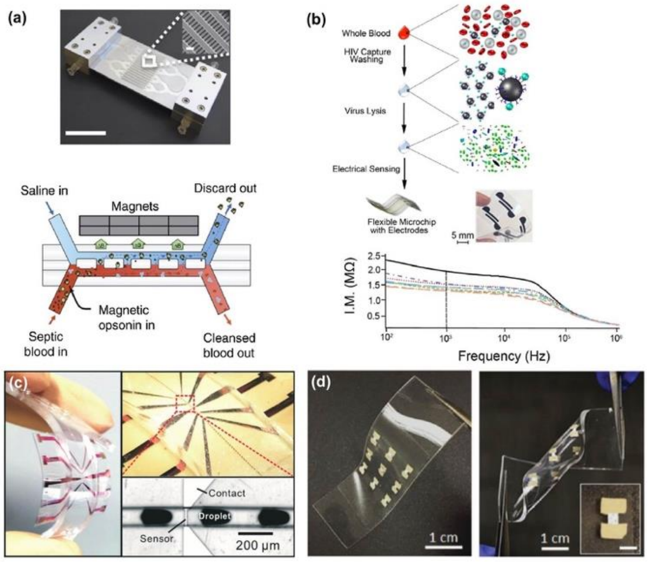

Fig. 1 **(a)** An electronic microfluidic device (top) for removing pathogens from blood (bottom), which captures and concentrates a target particle only [9]. **(b)** A flexible electronic sensor for detection of HIV [10]. **(c)** Photo of a FHE showing a magnetoresistive analytical device [11]. **(d)** Photo of a flexible photodetector array under applied mechanical deformation [12].

2. *Skin-like electrodes for FHE*

A long-term, persistent HMI requires a highly conformal, reliable electrode that makes the direct contact to the human skin. As an example, **Fig. 2(a)** presents a new type of wearable, “skin-like” electrode (200 nm in thickness and 5 μm in width) that can achieve conformal lamination onto the silicone elastomer skin replica [3]. We utilized this ultrathin, conformal design criterion for intimate device lamination on the skin for acquisition of high-fidelity biopotentials from skeletal muscles [1], heart [3], eyes [2], and brain [13]. The effective modulus of the skin-like electrode was investigated considering the nanomembrane metal (Au) component. Recently, we introduced a bio-inspired, self-similar fractal structure to build a highly flexible and stretchable electrode [14]. Fractal curves are mathematically defined paths that exhibit self-similarity across multiple scales; greater or lesser space-filling density is quantitatively achieved by varying the number of iterations. **Fig. 2(b)** shows a representative example of a fractal ‘Peano’ curve that makes multiple types of stretchable electrodes. We examined six different fractal layouts, mainly focusing on ‘Peano’ curves, to discover their contribution to enhancing mechanical behavior. Organized in a fractal layout, a silicon nanomembrane structure demonstrated stretchability of more than 50%, which far exceeds that of skin (10% – 20%) [14].

This proven advantage of the fractal structure was successfully adapted to design an ultrathin, membrane electrode for a long-term, high-quality electroencephalography (EEG) recording [13]. **Fig. 2(c)** shows the auricle electrode where a ‘Peano’ fractal structure makes the conformal lamination onto the skin. The soft electronic device was successfully mounted on the auricle having the contoured, curvilinear geometry for high-quality EEG recoding without conductive gels. The locations of auricle and mastoid are attractive in the EEG measurement since they have little hair, but are inconspicuous to the user and observers. Since the brain-enabled HMI establishes a new communication opportunity between the human and external devices, acquiring EEG from these locations can be useful for individuals with motor impairments. Moreover, it can be combined with other smart electronics to enrich the living quality of general population. Among many different methods of recording brain signals, EEG detection is the most popular technique due to its simplicity, cost-effectiveness, and high temporal resolution.

Fig. 2(d) presents an example of a brain-enabled HMI with wearable FHE where the electrode is mounted on the auricle and mastoid areas as shown in **Fig. 2(c)**.

One of measurable brain signals in a non-invasive way, the steady-state visual evoked potential (SSVEP), has been widely studied in HMI since different types of SSVEPs can be easily generated by visual stimulation. The demonstration of an SSVEP-based HMI started with optimal positioning of electrodes in order to maximize the signal quality. The text speller interface consisted of visual stimulation in the form of a speller grid with alphanumeric characters flashing at different frequencies and observed by a volunteer subject, whose EEG signals were automatically analyzed to extract SSVEPs. To distinguish different EEG signals, we utilized a canonical correlation analysis (CCA), a well-known method for finding correlations between two variables [13]. The CCA-based classifier determined the user's desired alphanumeric character as each visual target flickered at a unique frequency. A subject wearing the soft epidermal electrodes attempted to spell the word "computer" with the assistance of word prediction algorithms (**Fig. 2(d)**). The result showed the average spelling speed was 2.37 characters per minute using the EEG device, which shows a high performance, considering the non-invasive recording on the mastoid area, not directly on the hairy visual cortex that most of research works have focused.

3. *Persistent Wearable HMI*

Recent remarkable progress in the development of wearable FHE has offered non-invasive, highly sensitive interactions between human and machines. Mechanically compliant, skin-wearable FHE enables conformal contact to the human skin in a non-invasive way, while recording important physiological data. The biopotentials, measured from the skin-mounted electrodes, can be used to control a humanoid robot, drone, prosthetic hand, display interface, electronic wheelchair, and more. A few representative examples in **Fig. 3** captures the most recent HMI applications, controlled by FHE-enabled biopotentials. The main advantage of FHE in such examples is their portable, comfortable, and ergonomic arrangements via a low-profile, miniaturized electronic circuit, conformal electrodes, and data recording and management system.

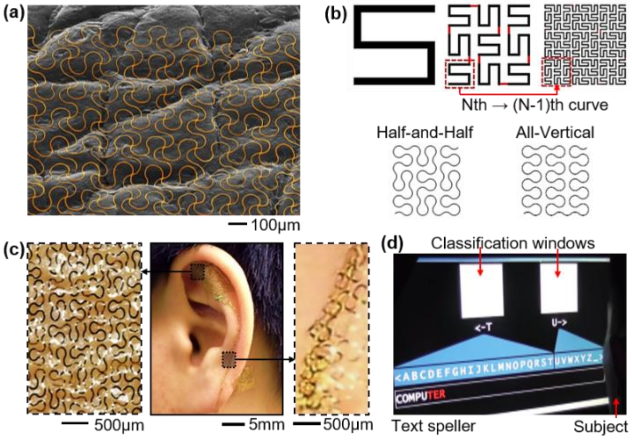

Fig. 2 Skin-like electrodes and associated FHE for a persistent HMI. **(a)** Colorized scanning electron microscope image that shows conformal contact of the electronics (gold) on the skin replica [3]. **(b)** Self-similar, fractal curves to construct the conformal electronics. Multiple iterations and linking of the Peano curves were used for high-density space filling [14]. **(c)** Skin-like FHE mounted on the areas of the auricle and mastoid (middle) for EEG recording; the device includes a fractal electrode (left) and stretchable interconnect (right) [13]. **(d)** A text-speller interface, designed to use EEG signals (SSVEP), measured by the auricle mounted electronics [13].

A soft, skin-like sensor system in **Fig. 3(a)** [15], directly mounted on the skin via van der Waals interactions, offers unobtrusive, comfortable HMI for sensorimotor prosthetic control of a humanoid robot. The multifunctional device has open-mesh structured, microfabricated electrode and sensor, integrated on an elastomeric membrane, which is mechanically flexible and stretchable to accommodate the strain from the skin deformation. The gold nanomembrane-based system has advantages of simultaneous sensing and electrical stimulation, which makes sensorimotor control of a robot arm. With the stimulation feedback, a subject who wears the device can grip a water bottle in a controlled manner to prevent collapse. A similar device [1] that makes an intimate contact with the skin (**Fig. 3(b)**) offers a high-fidelity recording of surface EMG on forearms. Bimanual gestures, recorded by two sets of electrodes on forearms generate different signal commands to control a drone (e.g., quadcopter). There were four commands, generated by a signal classification algorithm that used electomyogram data on the skin. With an optimized electrode design and placement on the target muscle, this work demonstrated 91.1% classification accuracy with four classes.

Fig. 3(c) presents a "smart" prosthetic hand [16] with artifical skin and embedded soft sensors, enabled by stretchable silicon nanoribbon on a silicone elastomer (PDMS). A high performance, single crystalline silicon designed a highly sensitive device with strain, pressure, and temperature sensors. The electronic skin on the prosthetic hand with the soft sensor package demonstrated capabilities of hand shaking, keyboard typing, ball grasping, and feeling surface temperature in daily lives. Another wearable set of FHE embedded in a headset [17] with EEG electrodes demonstrated the feasibility of hybrid brain-controlled computer (**Fig. 3(d)**). In this study, the wearable head set recorded steady-state visually evoked potentials to control a computer interface, which can be directly usable for severely disabled people who cannot use their arms and hands. The event-related synchronization of EEG can be used in many applications such as text spelling interface, computer control, wheelchair control, and more. Among those, a hands-free control of an electronic wheelchair has gained a great interest in rehabilitation and aging societies. Patients with Parkinson's disease or amyotrophic lateral sclerosis experience paralyzed voluntary muscles and significantly reduced motor strength.

In addition to the EEG-base method, eye movement can be utilized to control a wheelchair. A wearable FHE shown in **Fig. 3(e)** [18] enables a non-invasive, comfortable arrangements to measure eye movements via electrooculogram (EOG) recording. In this work, the wearable system included forehead EOG electrodes on a headband along with Bluetooth-based wireless telemetry. A subject wearing the electrode system successfully drove a power wheelchair through an 8-shaped driving course without a collision with obstacles. Collectively, soft, lighweight materials play a key role in the design of wearable, comfortable FHE. The mechanical compliance of the soft sensors makes conformal and intimate contact to the skin for high-fidelity recording of non-invasive biopotentials for various HMI applications.

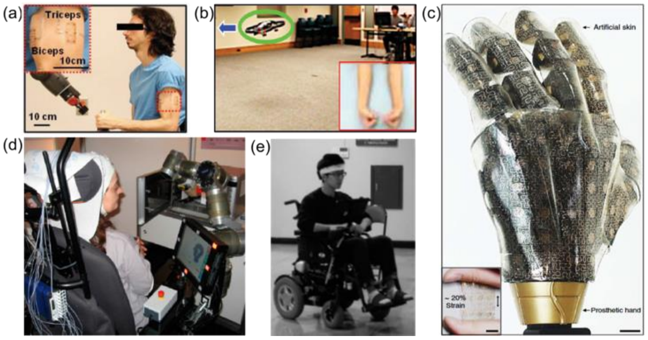

Fig. 3 Flexible hybrid electronics for applications in human-machine interfaces. (**a**) EMG-enabled control of a humanoid robot [15]. (**b**) Bimanual gestures and their EMG signals, interfacing with a quadcopter [1]. (**c**) Sensor-laden bionic hand, instrumented with silicon nanoribbon [16]. (**d**) Wearable headset and EEG recording for a brain-interfaced system [17]. (**e**) Recording of EOG via a wearable forehead system for a wheelchair control [18].

III. Conclusion

This short paper summarizes the recent advancement of flexible hybrid electronics (FHE) for smart and connected bioelectronics, which have found many important applications in seamless health monitoring and persistent human-machine interfaces (HMI). This new class of soft materials and system integration technologies enables a significant advancement on the wearable applications for a smart, home healthcare, and ergonomic rehabilitation and prosthesis. We reviewed recently developed health monitoring systems that integrate nano-microfluidic devices with flexible electronics to offer portable health monitoring. The key properties of soft material interfaces in the device and/or with the human skins offered to design highly sensitive FHE. We discussed the details of functionality and sensitivity of skin-mounted electrodes and applications in persistent HMI. Areas for further development of such FHE include enhanced device functionality and extended HMI applications. Devices incorporating wireless energy harvesters and automatic data processing algorithms with machine learning methodologies would offer an ideal environment for portable, in-home recording of health conditions during daily activities. A smartphone application to directly communicate with the wearable FHE would create new opportunities to develop unobtrusive, comfortable health-monitoring and HMI systems.

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