2015

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Woon-Hong Yeo  
Mechanical Engineering, VCU, whyeo@vcu.edu

Yongkuk Lee  
Mechanical Engineering, VCU

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Skin-Like Electronics for a Persistent Brain-Computer Interface

Yongkuk Lee
Department of Mechanical and Nuclear Engineering, School of Engineering, Virginia Commonwealth University, Richmond, VA 23284, USA
E-mail: ylee3@vcu.edu

Woon-Hong Yeo, corresponding author
Department of Mechanical and Nuclear Engineering, School of Engineering, Virginia Commonwealth University, Richmond, VA 23284, USA
Center for Rehabilitation Science and Engineering, School of Medicine, Virginia Commonwealth University, Richmond, VA 23298, USA
E-mail: whyeo@vcu.edu

The authors declare that there are no conflicts of interest
Abstract
There exists a high demand for a continuous, persistent recording of non-invasive electroencephalograms in both clinical and research fields. Head-cap electrodes with metal conductors and conductive gels are widely used and considered as the gold standard for such measurement. This physical interface, however, is poorly suited to uninterrupted, long-term use due to the uncomfortable rigid electrodes, skin irritation due to the gel, and electrical degradation as the gel dries. These issues can be addressed by using a newly developed, dry form of electronics. Here, we briefly review a class of soft electronic technology in the aspects of mechanics, materials, and its capabilities for a long-term recording of electroencephalograms and a brain-computer interface (BCI). We summarize the progress in the development of a skin-like electronic system with a focus on key mechanical factors to achieve conformal skin contact. The design of hard electronics, integrated with soft membranes, uses deterministic fractal motifs to offer bending and stretching mechanics. We also introduce a most recent example of such electronics, an ‘auricle-integrated system’, which includes a strategy of conformal integration on the complex surface topology, a quantitative study of biocompatibility, and an application as a persistent BCI.

Keywords
skin-like, soft electronics, electroencephalogram, brain-computer interface
**Introduction**

Electroencephalography (EEG) is a non-invasive technique to evaluate human brain activity [1]. For example, interpretation and characterization of EEG signals [2] can be exploited in clinical study to diagnose various brain diseases including epilepsy [3], narcolepsy [4], brain lesions [5], and tumors [6]. In addition, EEG facilitates the emerging technology of brain-computer interfaces (BCI), which provide direct communication between the brain and electronic systems. While EEG possesses many advantages including a high temporal resolution and simple, low-cost signal recording [7], the development of a continuous, uninterrupted EEG system still remains a big challenge in BCI research. The gel electrode technique that is the gold standard for EEG recording has limitations for prolonged, long-term use [8-10], mainly due to the electrode material and electrolyte gel. Rigid, flat electrodes, fixed on the skin with tape or a cap, cause user discomfort over long-term use. Furthermore, the conductive gel dries out and causes significant degradation of signal quality [11, 12] and skin irritation (erythema) [8, 13] over a few hours of use. The typical EEG recording setup, even with advanced wireless technology [14, 15], still incorporates bulky wires and rigid electronic systems, which hinders long-term signal recording, especially during normal daily activity.

To address these problems, a number of alternative means have been developed such as dry-contact needle electrodes and non-contact capacitive electrodes [16-18]. The dry electrodes without the use of an electrolyte gel have resolved some issues that are directly related to the gel. However, they are still problematic for long-term recording due to high levels of motion artifact noise, which dramatically reduce the signal-to-noise ratio (SNR) [19]. Tight securing of the electrode to the skin could reduce the artifacts, but this causes discomfort and pain associated with the pressure [20]. Recent studies on capacitive, indirect contact electrodes demonstrated the possibility of long-term EEG recordings [21, 22]. Incorporation of a soft, skin-compatible material (e.g., silicone) between the electrode and the skin provided a high level of comfort. However, the bulky structure and inherent high impedance due to the dielectric layer need to be further improved for extended, everyday use.

Recently, there has been remarkable progress in electrode development with the use of ultrathin and compliant materials. The newly developed system, referred to as epidermal electronics systems (EES) [23], enables conformal contact of electrodes to the skin without gels, and thus it offers comfortable, non-invasive recording of important physiological data such as electrophysiological potentials [24-26], mechanical strain [27], temperature [27, 28], and hydration [29, 30]. As an example, Figure 1(A) shows an EES that has multifunctional capabilities to record various physiological signals on the skin [27]. Figures 1(B) – (G) illustrate the overall process of the device fabrication and lamination on the skin. Figure 1(H) captures the mechanical stability and long-term wearability of an EES on the skin (forearm) upon dynamic skin deformation for a week. The electronic system, made of metallic nanomembrane circuits and electrodes, is integrated with a soft, ultrathin, stretchable elastomeric membrane. Physical properties of such a device are well matched with the epidermis, which allows intimate contact on the skin via van der Waals forces alone. In this short review, we summarize the design criteria, characteristics, and functionality of an EES for various applications.
Figure 1. Multifunctional epidermal electronic systems (EES) on the skin [27]. (A) Optical images of an EES including an electrophysiological (EP) sensor, temperature sensor, and strain sensor. (B) The microfabricated electronics on a carrying Si wafer. (C) Retrieved electronics on an elastomeric stamp. (D) Transfer printing of the electronics onto the skin facilitated by a sprayed glue layer. (E) Retrieved electronics on a spray-on-bandage/polyvinyl alcohol (PVA). (F) Printed electronics on the skin by dissolving the PVA in water. (G) Application of an additional layer of spray-on-bandage for the device encapsulation. (H) EES mounted on the forearm (left), mechanical compression and extension of the EES with the skin (center), and demonstration of long-term wearing for a week with normal living activities (right).
Mechanics and materials of skin-like electronics

In the fundamental aspects of the mechanics, the effective modulus and total thickness of the device are key factors to determine the required bendability and stretchability of a skin-like electronic device. An analytical calculation [25, 32] considers the total interfacial energy between an EES and the skin:

\[ U_{\text{interface}} = U_{\text{EES\_bending}} + U_{\text{skin\_elasticity}} + U_{\text{adhesion}} \]  

(1)

where \( U_{\text{EES\_bending}} \), \( U_{\text{skin\_elasticity}} \), and \( U_{\text{adhesion}} \) are the bending energy of the EES, the elastic energy of the skin, and the adhesion energy of the contact, respectively. The simplified expression is described as:

\[ \frac{\pi E_{\text{skin}} h_{\text{rough}}}{\gamma_{\text{EES}} \lambda_{\text{rough}}} - 16 < 0 \]  

(2)

where \( E_{\text{skin}} \) is Young’s modulus of the epidermis, \( h_{\text{rough}} \) is the skin amplitude, \( \lambda_{\text{rough}} \) is the skin wavelength, \( \gamma_{\text{EES}} \) is the effective work of adhesion, and \( EI_{\text{EES}} \) is the bending stiffness of an EES. The theoretical analysis in the equations (1) and (2) indicates that the total interfacial energy is related to the bending stiffness of an EES, which includes a variable factor, the device thickness. Assuming the skin has a modulus of ~130 kPa and amplitude and wavelength are ~100 µm and ~140 µm, respectively, the total interfacial energy becomes zero at the critical device thickness of about 25 µm [25]. The analysis indicates that an EES below the critical thickness forms intimate, conformal contact with the skin, which was verified by an experimental study using scanning electron microscopy. Figure 2(A) presents an example of conformal skin electronics (200 nm in thickness and 5 µm in width), mounted on the skin replica (polydimethylsiloxane) [25]. Thus, we utilized this design criterion (thickness < 25 µm) for intimate device lamination on the skin for acquisition of high-fidelity physiological signals. The effective modulus of an EES must also be investigated since the device integrates electrical components having a high modulus (Au: ~97 GPa) with a soft membrane (silicone: ~65 kPa) [32]. As the modulus of the hard material governs the overall effective modulus of the device [23], careful attention is required to the design layout [26].

Recently, we introduced a bio-inspired fractal geometry to build mechanically enhanced EES [31]. 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 of a particular template [33]. Figure 2(B) (top) shows an example where the N\textsuperscript{th} ‘Peano’ curve includes nine copies of the (N – 1)\textsuperscript{th} curve by linking together as a single fractal line. To avoid elastic stress concentrations, the sharp corners of the fractals were replaced with arcs. The appropriate arrangement of different orders of ‘Peano’ curves could fill the space in, for example, letters of the alphabet or geometric shapes. In a prior study [31], we examined six different fractal layouts, mainly focusing on ‘Peano’ curves, to discover their contribution to enhancing mechanical behavior. Experimental and numerical simulation data showed that fractal-based structures can be freely tailored to control elastic stretchability, depending on requirements. Organized in a fractal layout, a silicon nanomembrane demonstrated stretchability of more than 50 %, which far exceeds that of skin (10 – 20 %) [34]. Furthermore, a variety of fractal designs showed great potential for a broad range of biomedical applications, including a non-invasive heart monitoring/temperature sensor, an electronic heater, and radio frequency devices.

This proven mechanical advantage of fractal layouts was adapted to design the ultra-bendable auricle-integrated system for long-term, high-quality EEG recording [13]. Figure 2(C) presents the soft electrode system where 3\textsuperscript{rd}-order ‘Peano’ fractal curves form electrodes (Half-and-Half design) and
stretchable interconnect (All-Vertical design). The interconnect adopted all-vertical layouts to maximize the uniaxial stretchability along their longest axes. By contrast, electrodes used half-and-half layouts, which consist of unit cells with alternating orientations, to balance the stretchability in all directions. As a result, the ultrathin, compliant device on a thin elastomeric membrane (Young’s modulus: 20 kPa and thickness: 3 µm) demonstrated high levels of both elastic bendability (180º) and stretchability (~50 %) with only 0.25 % maximum principal strain on the metal (Au).

The soft device was successfully mounted on the auricle [13] in a way that ensures conformal contact and robust adhesion for high-quality EEG recording, even without gels. The locations of auricle and mastoid are attractive in the EEG measurement since they have little hair and offer unobtrusive, hidden places for device lamination. The ultrathin, stretchable electrode system could address the main challenge of device mounting on the curvilinear, sophisticated geometry of the auricle area. Conformal mounting of the device was attempted on different regions of the ear, including the fossa triangularis, crura of antihelix, helix, and lobule, to demonstrate the excellent bendability and stretchability of the device.

In addition, another example of a skin-like electronic system, fractal structured temperature sensors [28, 35], demonstrated highly conformal mounting on the skin. In a clinical study [35], the electronic device could laminate gently and reversibly on the sensitive tissues involving surgical wounds for quantitative temperature and hydration monitoring and it also showed a potential for therapeutic use such as hyperthermia treatment of skin cancers [35-37].

Figure 2. Skin-like electronics for a persistent BCI. (A) Colorized scanning electron microscope image that shows conformal contact of the electronics (gold) on the skin replica [27]. (B) Self-similar, fractal (‘Peano’) curves to construct the conformal electronics. Multiple iterations and linking of the Peano curves were used for high-density space filling (top) and unit cells of ‘Half-and-Half’ and ‘All-Vertical’ patterns were used in the design of soft electronics (bottom) [31]. (C) Skin-like electronics 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) BCI for a SSVEP-based text speller [13].
**Long-term EEG for a persistent BCI**

We explored a soft, conformal electrode system, designed by mechanical analysis, to record long-term EEG data on the scalp. The device fabrication uses a newly developed approach that combines conventional microfabrication techniques and transfer printing for hard-soft material integration. Details of the fabrication procedure of such soft electronic system appear in a recent report [38]. The fabricated device, composed of dry, open-mesh, conformal electrodes on an ultrathin, stretchable membrane, was the key feature for a persistent BCI [13]. The EES was worn continuously through a subject’s normal daily activities, including exercising, showering, and working; EEG alpha rhythms and P300 wave, event related potential (ERP), were collected over the course of 2 weeks and 2 days, respectively. In prior works [13, 27, 39], we applied a protective layer of spray-on bandage (medical grade) to the device laminated on the skin for prolonged recording of physiological signals up to 2 weeks. A similar approach facilitated continuous EEG recording by using the spray-on-bandage once or twice a day, which provided a skin-friendly, breathable, water-proof protective environment for the EES [40]. An important aspect of this strategy is that the device establishes strong, intimate integration with the body without causing any discomfort, adverse side effects, or mechanical constraints during daily activities. While the electrodes remained on the skin throughout the testing process, physical contact for EEG measurement was made by van der Waals interactions using a silicone-based electrical connector. The soft, flexible connector offered reversible, but low resistance electrical connection between the electrode and data acquisition system. The experimental results showed prolonged, but high-fidelity, persistent recording of EEG signals. The SNR values were nearly identical across all recording periods and comparable to the signals captured from freshly prepared conventional wet electrodes with conductive gels.

For a persistent BCI to be wearable for more than a few days, the device’s skin interface has to meet the criteria of biocompatibility. We designed an EES with well-characterized materials like silicone and polyimide, both shown to be skin-friendly [27] and even clinically usable [35] materials without any deleterious effects on the skin. In addition, a cell viability assay and infrared thermographic (IRT) measurement provided quantitative validation of the device's biocompatibility. For the cell viability assay, keratinocyte cells were cultured both on the device and in a cell culture dish. Observation of the cultured cells via fluorescence microscopy suggested that the device is non-cytotoxic and skin-friendly. Comparative assessments of biocompatibility between the epidermal EEG sensor device and conventional wet electrodes were conducted using IRT and contact microscopy. The observations indicated that the skin-like electronics cause no adverse effects such as erythema, rash, or swelling during the testing period (2 weeks). On the contrary, the conventional wet electrodes with electrolyte gels caused erythema, clearly detectable as an elevated skin temperature after 1 day.

The soft technology-enabled BCI can be further improved with tripolar concentric ring (TCR) electrodes. This electrode design enhances spatial resolution, as it consists of three ring-shaped electrodes in an area comparable to that of a single conventional electrode [41]. To assess its potential use in EEG measurement, epidermal TCR electrodes consisting of three layers were constructed on a 3 µm-thick elastomer. The TCR electrodes formed conformal contact to the curved surface of the auricle and mastoid to record EEG alpha rhythms. The results showed that each electrode ring is capable of independently measuring EEG alpha rhythms, so that a system of these electrodes can provide more spatially dense data than conventional geometries. Epidermal capacitive electrodes were also demonstrated by adding a 3 µm-thick elastomeric insulating layer on top of Au electrodes, which offered additional user safety by avoiding direct electrical loading of the skin. The complete enclosure of the electrode with an elastomer ensured reusable of the device after cleaning with soap and water.

Since a BCI establishes a new communication channel between the human brain and external devices, not only it can be useful for individuals with motor impairments [42], but also it can be combined with other interfaces to enrich human life [43]. Even though a variety of techniques including electrocorticography [44], magnetoencephalography [45], and functional magnetic resonance imaging [46] can be used for a BCI, EEG is the most popular technique due to its simplicity, cost-effectiveness, and high temporal resolution [47]. For example, the auricle interface device [13] was successfully
integrated with BCI2000 software to build a text-speller system. Figure 2(D) presents the interface that uses EEG signals recorded by the soft electrode system on the auricle and mastoid, shown in Figure 2(C). The first method, the steady-state visual evoked potential (SSVEP), has been widely studied in BCIs, since different SSVEPs can be generated with visual stimuli of different frequencies with high SNR [48]. The demonstration of an SSVEP-based BCI started with optimal positioning of electrodes in order to maximize SNR. 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. The classification was based on canonical correlation analysis (CCA), a well-known method for finding correlations between two variables [48]. 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 (Figure 2(C)) attempted to spell the word “computer” with the assistance of word prediction algorithms (Figure 2(D)). The result showed the average spelling speed was 2.37 characters per minute using the EEG device. A speller BCI based on a second method, the so-called P300 ERP, was also tested. This signal is elicited by rare, task-relevant stimuli, and is typically observed about 300 ms after the stimulus appears [42]. For example, if a user selects a target, the P300 is evoked when the stimulus including the target is present. In the aforementioned experiment, this took the form of a sequential display of the characters to choose from within the speller. EEG recordings using the soft device clearly showed P300 ERP in response to flashing of the target characters.

Conclusions
This short review summarizes the recent development of a skin-like electronic system in the aspects of mechanics, materials, and applications toward a BCI. This new class of soft interface technology enables the development of bio-interfaced stretchable sensors and actuators. As an example in a BCI, we reviewed a soft electrode system that uses EEG signals from the non-hair-bearing scalp, auricle and mastoid, for a text speller. These long-term-wearable dry electrodes demonstrated persistent utility for measurement of EEG alpha rhythms for up to 2 weeks, as well as for use in a text spelling interface based on SSVEP and P300 ERP. Areas for further development include enhanced device functionality and extended BCI applications. Devices incorporating wireless power and data transmission components would offer an ideal environment for portable, in-home recording of EEG during daily activities. A smartphone app to directly communicate with the soft devices would create new opportunities to develop unobtrusive, comfortable health-monitoring systems. Possible applications of the soft electronics-based BCI include neuroprosthetics, diagnosis of neurological disorders, neurogaming (e.g. interacting with a game console without a manual remote controller), and neuro-assisted tutoring for individually tailoring the learning process.

Acknowledgments
We thank Graham Kelly and Farheen Syeda for useful discussions. W.-H.Y. acknowledges startup funding from the School of Engineering, Virginia Commonwealth University (VCU) and we thank the research development support from VCU Center for Rehabilitation Science and Engineering.

References


