ElectroDermis: Fully Untethered, Stretchable, and Highly-Customizable Electronic Bandages

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ABSTRACT

Wearables have emerged as an increasingly promising interactive platform, imbuing the human body with always-available computational capabilities. This unlocks a wide range of applications, including discreet information access, health monitoring, fitness, and fashion. However, unlike previous platforms, wearable electronics require structural conformity, must be comfortable for the wearer, and should be soft, elastic, and aesthetically appealing. We envision a future where electronics can be temporarily attached to the body (like bandages or party masks), but in functional and aesthetically pleasing ways. Towards this vision, we introduce *ElectroDermis*, a fabrication approach that simplifies the creation of highly-functional and stretchable wearable electronics that are conformal and fully untethered by discretizing rigid circuit boards into individual components. These individual components are wired together using stretchable electrical wiring and assembled on a spandex blend fabric, to provide high functionality in a robust form-factor that is reusable. We describe our system in detail—including our fabrication parameters and its operational limits—which we hope researchers and practitioners can leverage. We describe a series of example applications that illustrate the feasibility and utility of our system. Overall, we believe ElectroDermis offers a complementary approach to wearable electronics—one that places value on the notion of impermanence (*i.e.,* the opposite of tattoos and implants), better conforming to the dynamic nature of the human body.

CCS Concepts

• Human-centered computing~ *Ubiquitous and mobile computing systems and tools.*

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Figure 1: We present *ElectroDermis* a holistic fabrication approach for fully untethered, stretchable, and on-skin compliant wearable electronics. Here, we show several example applications, including a temperature mask, vital monitoring earrings, context-sensitive necklace, motion tracker, wound monitor, and environment-aware bracelet.

KEYWORDS

On-skin devices; Wearable electronics; Fabrication; Spandex

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1 INTRODUCTION

Wearable electronics—from smartwatches to wireless earbuds, to smart glasses and electronically enhanced tattoos—are starting to emerge as viable computing platforms, unlocking unique applications that bring computation closer to the human body [16, 18, 25]. Most commercially available wearables provide a high level of functionality but are primarily composed of traditionally rigid materials (*e.g.,* metals and hard plastics), limiting their placement to locations of low movement or flexibility, diminishing overall functionality and signal quality [8]. Recent advances in materials and mechanics have resulted in the development of soft, "skin-like" devices closely matching the mechanical properties of biological tissue [25]. These have spawned new applications in health monitoring, on-body user interfaces, and novel interactions with the environment. However, these efforts often have low functionally as compared to their rigid counterparts, as they typically only focus on a single component of the overall system (*e.g.,* sensing or actuation), have limited stretchability, require tethered connections, or are ultimately limited by cumbersome and impractical equipment that hinders overall mobility.

In this work, we present *ElectroDermis,* an efficient, holistic fabrication approach to push the practical boundary of on-skin electronics and wearable computing by bridging the gap between high functionality and stretchable and compliant on-body electronics (Figure 1). In contrast to other approaches that largely focus on a single on-skin component (*e.g.,* sensor, actuator), we combine a network of all the necessary electronic components for sensing, signal processing, wireless communication, and power infrastructure to create an untethered on-skin electronic device that is small, flexible and stretchable enough to resemble *electronic bandages.* To achieve high functionality, individual electronic components are wired together using stretchable electrical wiring. These circuits are then assembled on a spandex-blend fabric substrate, to improve robustness and durability, while allowing the electronic bandages to be reused. A variety of on-body soft-matter printed circuit boards are created, illustrating the capabilities of the ElectroDermis fabrication approach. All bandages are created in less than one hour, attached to the body using a medical grade adhesive, and can be temporarily worn for hours or days. In contrast to traditional bandages or other on-skin devices, the fabric substrate enables the skin adhesive to be replaced after use, allowing the bandages to be reused.

To realize this vision, we created an interactive design tool for end users. First, our tool provides a method to easily select the target body region from a predefined 3D model of the human body or a 3D scan of the wearer. Next, the selected 3D surface is parametrically cut and flattened to provide minimal distortion. The electronic components are then placed on the flattened 2D pattern and a baseline curve is prescribed between each of the electronic components for electrical wiring based on a predefined circuit schematic. To enable the copper electrical wiring to be stretchable, our design tool automatically superimposes a wavy, serpentine architecture based on the baseline curve specified by the designer.

We demonstrate our holistic fabrication approach through a series of examples, across different locations on the human body, with varying complexity and artistic expression. The selected locations are suited to a variety of high-functionality sensing modalities (*e.g.,* heart rate, body temperature, wound healing status) and environment interactions (*e.g.,* color changing jewelry, health status) made possible with ElectroDermis. Our paper makes the following contributions:

1. An efficient, holistic fabrication approach and software design tool for creating untethered, highly-functional and stretchable (strain > 60%) electronic devices that conform and adhesively bond to the human body. Specifically, we advance the state-of-the-art by introducing a fabric layer to the fabrication process, increasing robustness, durability, and reusability.
2. An automated software design pipeline for generating highly customizable, stretchable electronic bandages for any surface, to improve adhesion and conformability to the surfaces of the human body.
3. We introduce a series of illustrative embodiments built from our fabrication system that highlight fully untethered wearable electronics that are stretchable and conformal, highly-functional, and aesthetically pleasing.

The rest of this paper describes key related work in this space, our detailed design and fabrication process, evaluations, and a series of example applications highlighting the feasibility and utility of *ElectroDermis*.

2 RELATED WORK

Our work intersects with several areas in HCI and material science. Here, we outline primary areas that are most relevant—on-body fabrication tools, rigid on-body devices, and stretchable, adhesive materials for on-body applications.

2.1 On-Body Fabrication Tools

To provide access to complex 3D surfaces on the human body, researchers have created new design tools for designing and creating interactive 3D objects. These design tools have led to a variety of fabrication methods and tools, such as sewing and water-transferring [12], cutting and water-transferring [14], inkjet printing [6], inkjet printing and water-transferring [27], screen-printing [32], and 3D printing [7, 29]. We build upon this body of work by using origami folding algorithms to transform between 3D and 2D surfaces and propose a new multilayer lamination-based fabrication method to efficiently create wearable electronic devices that conform to complex, on-body surfaces.

2.2 On-Body Devices

On-body devices offer a unique computational platform for user interaction. Unlike traditional computers, they are mobile, always available, yet highly constrained. In the HCI domain, the biggest challenge in this space is finding the right balance between function and practicality— minimal instrumentation is desired, but comes at the cost of functionality, and vice versa. Furthermore, since these devices are also worn by the user, they can become an extension for self-expression, and thus aesthetics [14, 28], which has become an increasingly important goal. Many research projects, especially in HCI, have investigated this growing area. One angle of attack is through novel sensing *i.e.*, inventing small yet accurate sensors and novel platforms that work particularly well on the body [6, 13, 17, 20, 22]. To further improve wearability, electronics can be removed from their rigid enclosures and the individual electronic components can be placed on the body surface [12]. While highly-functional, these previous efforts primarily focus on devices that are primarily composed of rigid materials, limiting their placement on the human body. Beyond sensing, a complementary approach is to formalize interaction vocabularies and desired futures for on-body and wearable interactions [10, 18, 33], or to empower others to make wearable devices easier to build [14, 32]. Our research draws inspiration from these prior works, and we aim to make contributions on the latter two (*i.e.*, offering a desired future for creating untethered, highly-functional wearable electronics, and making that vision easier to achieve using our fabrication system).

2.3 Stretchable and Adhesive Materials

Outside of the HCI domain, our work intersects with research in material science, specifically in the development of tools and fabrication methods for creating stretchable and adhesive materials. Most similar to our work are fabrication processes that combine adhesive substrates with electronics, creating novel on-skin interactive applications [10, 32, 34]. Despite their extraordinary potential, these efforts typically focus on a single component of the overall system (*e.g.* sensing [16]) and rely on rigid, bulky external hardware for signal processing. Consequently, these devices have limited function in natural, unconstrained environments. Most related to ElectroDermis is prior research on soft, multi-layered electronics for on-skin and bio-monitoring applications [19, 21, 22, 30, 31, 32]. Our work builds upon this research, by using a multi-layered fabrication approach to integrate advanced, miniaturized electronic components for signal processing, wireless communication, and sensing to provide high functionality in a single, untethered and highly stretchable, yet robust and reusable package. These electronic components are combined with stretchable electrical wiring and a spandex-blend fabric layer, enabling the rapid creation of wearable electronics through clever material selection (*i.e.*, combining stretchable and adhesive substrates). Furthermore, the process is also highly customizable through our end-user design tools.

3 DESIGN GOALS

As mentioned in the previous section, researchers have synthesized a series of design guidelines for wearable and on-skin electronics [14, 30], including skin compatibility, sensing and output modalities, on-body locations, aesthetic qualities, and overall practicality. ElectroDermis conforms to the design guidelines laid out by earlier work, while also bringing unique contributions to the state-of-the-art. Here, we describe our system in detail, which we hope designers and practitioners can leverage when building functional, robust and visually appealing wearable electronics.

4 ELECTRODERMIS: DESIGN PROCESS

We now describe our design and fabrication process in detail. Our system spans across a wide range of processes, from a custom software design tool, to material layering, hardware design, and end-user applications.

4.1 End-User Design Tool

The primary goal of our tool is to enable the design of electronic bandages that can conform to complex 3D (non-developable) surfaces, unlocking unique applications that bring computation closer to the human body. Our design tool enables access to only simple (*e.g.* forehead) but also complex (*e.g.* knee) surfaces on the human body. To provide access to a variety of surfaces, we leverage origami-based flattening algorithms to enable 2D sheets to conform to complex 3D surfaces without requiring deformation, buckling, or wrinkling. Our design tool was implemented in Rhinoceros 3D with Grasshopper and Human UI plugins. The tool provides a method for designing electronic bandages for geometrically complex regions of the human body that can be highly customized for a specific application or user. The design tool also generates all digital processing files for laser cutting and fabrication. The design process is divided into three steps that are detailed in Figure 2 and Figure 3.

Defining target region. In this process, we start by identifying a portion of user's body where the electronic bandage will be located. An existing mobile application (Trnio iPhone 3D scanner application) is utilized to generate a 3D model of the selected body region (Figure 2 a and b). The 3D model is then imported into Rhinoceros and the desired outline of the ElectroDermis electronic bandage is traced (Figure 2c). We recommend that the outline is drawn on a 2D plane instead of the 3D model for simplicity and novice CAD users. Next, the design tool projects the 2D contour onto the 3D model of the user and creates an editable 3D surface in the modeling environment (Figure 2d).

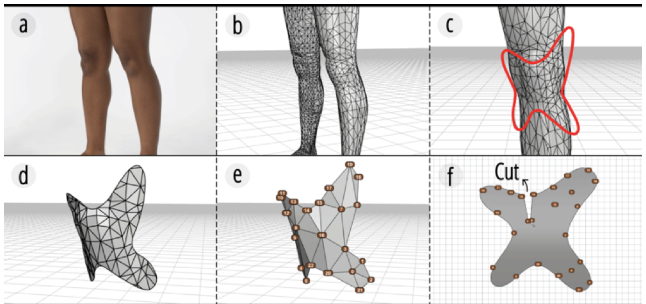

Figure 2: (a-b) A mobile device is used to 3D scan the target body location that will be used for rendering. (c) From the generated 3D model, a user defines the target reign on a 2D surface. (d) This curve is then projected onto the 3D model. (e) A reduced mesh is generated and (f) the 3D surface is parametrically cut and flattened to provide minimal distortion. The marks provide a mapping between the 3D and 2D surface.

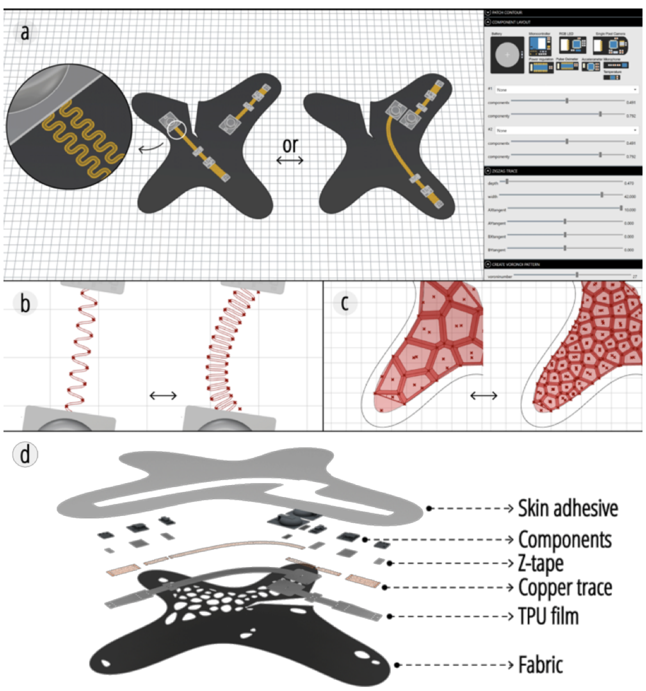

Figure 3: Design tool flow: (a) The designer arranges the electronic circuit on the flattened 2D surface. (b) The design tool automatically generates wavy, serpentine shaped electrical wiring between the components and provides significant freedom to customize the pitch, width, and radius of the trace. (c) After placing the electrical components and traces, the designer selects the region where they would like to generate voronoi holes. (d) The final file is exported and processed for laser cutting.

Automatic flattening. The ElectroDermis fabrication approach utilizes the lamination of flat materials to create highly customizable electronic bandages. Here we leverage origami-based flattening algorithms [1, 2] to parametrically cut and flatten a user selected region to provide minimal distortion when flattened (Figure 2e and f). These algorithms are integrated into our software design tool in Rhinoceros 3D, allowing the original 3D mesh to be flattened into a 2D pattern. Additionally, this algorithm automatically determines which segments to merge or cut.

To simplify the flattening process, the original 3D mesh is downsampled based on a user defined mesh count (Figure 2e). Based on our experiments, we recommend meshes with approximately 25 faces, which creates the right balance between comfort and look. The mesh is then cut and flattened using the origami-based algorithm (Figure 2f). Reference points are added to assist the user, to map the 2D surface back to the original 3D shape, if desired. Finally, users can smooth-out the edges of the bandage as desired.

Circuit customization. Each electronic bandage is composed of a battery, power regulator, microntroller, and digital sensor or LED that are wired together using a serial communication bus (Figure 4). The bandages are created by first selecting and placing the electronic components, which are stored in a database, on the flattened 2D surface. The circuit schematic is predefined within the design software and connection lines between the individual electronic components are automatically generated (Figure 4). The user can modify the contour of the initial connection lines between each of the circuit components using the design software tool. To enable the copper circuit to be stretchable, the design tool automatically generates a wavy, serpentine architecture based on the connection lines specified by the designer (Figure 3b) [4]. Users can adjust the location, path and geometry of the traces as long as the two end points are connected to the electrical components and no two traces intersect or overlap (Figure 3b). In general, wavy, serpentine shapes enable electrical wiring to be not only flexible but elastic with high initial electrical conductivity, without affecting data communication or power transmission between on-chip components.

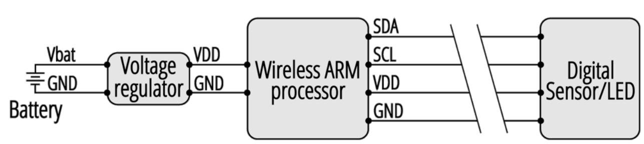

Figure 4. Predefined circuit schematic of ElectroDermis. Each electronic bandage includes ancillary power management, microcontroller, digital sensor or RGB LED.

Voronoi holes. Part of the goal of ElectroDermis was to design a fabrication process that enabled the creation of wearable electronics that were not only highly customizable and functional, but also aesthetically pleasing. To improve the aesthetics of the bandage, we leveraged Grasshopper's Voronoi plugin to create a visual pattern within a region that is defined by the designer. Based on the selected region, a lace pattern is automatically generated and allows the skin adhesive layer to penetrate through the electronic bandage and increase the adhesion to the skin. The plugin was refined to allow the user to manipulate the visual effects of the lace geometry, such as hole density and hole shape (Figure 3c). Additionally, other parametric design plugins could be easily integrated into the design software to provide alternative and personalized visual effects. Finally, after the design process has been completed, the digital fabrication files are generated for each of the individual layers within the electronic bandage (Figure 3d).

4.2 Multilayer Fabrication

Our multilayer fabrication approach utilizes commercially available materials that do not require surface modifications, chemical treatments, or curing. The layers used within the fabrication process provide robust lamination through inherent adhesion. Furthermore, the selected materials are readily available in roll format and can be easily processed by laser or die cutting, allowing the ElectroDermis multilayer fabrication approach to easily scale using more conventional roll-to-roll manufacturing methods for mass production. Furthermore, the combination of an elastic fabric substrate, the meandering (wavy, serpentine shaped) conductive traces and state-of-the-art miniaturized IC components aids stretchability and conformability to complex, non-developable surfaces found on the human body.

Electronic circuits. The electronic bandage is composed of a network of high performance integrated circuits that are wired together using a digital, 2-wire communication bus. To simplify the design and fabrication process, individual printed circuit board (PCB) modules are created for each integrated circuit (IC) within the network, shown in Figure 5. The modules also include all of the required supporting electronics (*e.g.* capacitor, resistor). Additional PCB modules can be easily created using new or pre-defined layout templates.

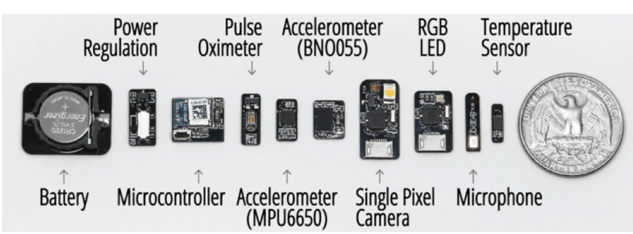

Figure 5. Photograph of the integrated circuit modules, including (left to right) ancillary power management, microcontroller, six digital sensors, and RGB LED.

A ARM Cortex-M4F processor with Bluetooth low energy (BLE) radio (nRF52, Nordic) is the central core of each electronic bandage and is responsible for signal processing, wireless communication, and control of the interactive components. Baseline code is initially uploaded to the processor, however the firmware can be easily modified after fabrication of the bandage using the over the air device firmware update (OTA DFU) tool provided by Nordic. To demonstrate the versatility of ElectroDermis, a variety of on-body sensors are selected that face the skin to noninvasively monitor biosignals (*e.g.* heart rate) or face outwards to monitor or interact with the environment (*e.g.* camera, LED). The subset of possible sensors that were used within this study are shown in Figure 5 and include a pulse oximeter (MAX30101, Maxim), high-fidelity accelerometer (MPU6650, InvenSense), 9-DOF position sensor (BNO055, Bosch), single pixel camera (TCS34725, AMS), MEMS microphone (SPH0645LM4H-B, Knowles), and temperature sensor (MCP9808, Microchip). The modules were created following the recommended application circuit, which can be found within the corresponding manufactures datasheet. While this is a small subset, the ElectroDermis fabrication approach could accommodate any digital sensor or analog sensor with analog front end (AFE). To provide information or interact with the environment, we created an RGB LED module that includes a microcontroller (ATMega328, Microchip) that is serially addressable, enabling full control of the LED and advanced interactions such as PWM fading. Finally, ancillary power management modules (*e.g.* battery and power regulation) were created and are shared between all of the components on the electronic bandage. We note that some of the sensors required two batteries wired in parallel.

Circuit interconnects. The network of IC modules are electrically wired together with stretchable electrical wiring. For this study, we selected highly conductive, 70 µm thick flexible copper-clad (FR7031, DuPont). To enable stretchability, the flexible copper-clad is laminated onto a silicone bed (Sylgard 184, Dow Corning) and patterned into a wavy, serpentine shape using a UV laser micromachining system (Protolaser U3, LPKF). The excess film is then removed and the remaining copper trace is bonded to a compliant thermoplastic polyurethane (TPU) film (3412, Bemis) using a heat press (120° C, 30 secs). The stretchable interconnects are then visually aligned andelectrically connected and adhesively bonded to the IC modules using an anisotropic, through thickness conductive tape (ECATT 9703, 3M).

Fabric substrate. Fabric is abundant and an integral part of everyday life—from artistic, to household, to industrial and scientific purposes. Here, we laminate the electronic circuit onto a spandex blend fabric substrate (120° C, 60 secs)

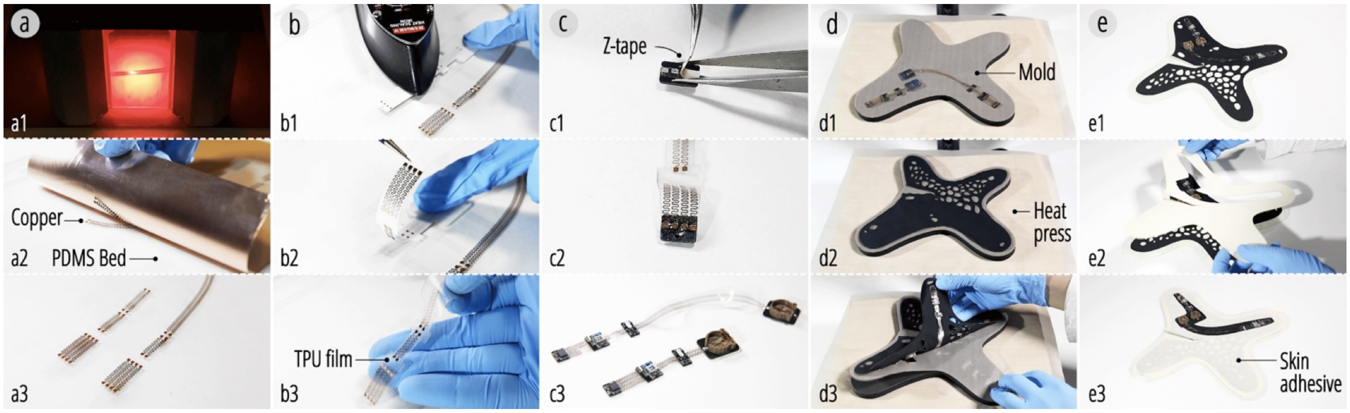

Figure 6: Multilayer fabrication process. (a) Flexible copper clad is processed using UV laser micromachining on a PDMS bed. (b) TPU film is laminated onto the copper traces and removed from the PDMS bed. (c) Z-axis tape is applied to the electrical components and bonded to the copper traces. (d) Electrical circuit is placed within foam mold and bonded to a fabric substrate using a heat press. (e) Medical grade skin adhesive is applied to the electronic bandage.

to provide increased robustness and durability, while allowing the electronic bandages to be reused. Most of the electronic bandages shown here were reused 10+ times without failure. This is in stark contrast to previous efforts, which are assembled on thin adhesive films or temporary tattoo paper. Use of these substrates requires disposal after use due to the electronic circuit being damaged during removal or lack of reusable medical grade skin adhesives. Furthermore, because of the ultra-thin film, these devices are often difficult to adhere to the body without self-adhesion (or clinging) as electrostatic forces become dominant.

Skin adhesive. Wearable electronics that directly adhere to the skin result in improved signal quality due to reduced motion artifacts and provide access to locations on the human body without unnecessarily diminishing the somatosensory system. For example, a sensor can be placed on the back of the hand or palm without requiring a glove that would diminish the users sense of touch. We use a transparent, medical grade adhesive film that is breathable, waterproof, and provides a sterile barrier (Tegaderm, 3M). Holes are laser cut in the location of the IC modules and the adhesive is then directly bonded to the fabric substrate. After use, the skin adhesive can be peeled from the fabric substrate and discarded. For reuse, a new adhesive film can be reapplied to the fabric substrate as before. The adhesive film provides robust adhesion to the wearer and enables temporarily attachment for hours to days.

Multilayer assembly. The ElectroDermis fabrication approach utilizes multiple layers of fl at materials that are readily accessible and purchased in roll format. Specifically, we select materials that are soft and highly extensible and due to their inherent pressure- or heat-sensitive adhesive characteristics provide robust adhesion upon lamination under light pressure or heat without any additional processing. The materials are first cut to size using a laser cutter. The materials are then visually aligned and laminated together using a heat press or light pressure. Advanced electronic components are integrated during the fabrication process using an anisotropic, through thickness conductive tape to create highly customizable electronic bandages for a range of applications. The fabrication process is detailed in Figure 6.

First, shown in Figure 6a, the flexible copper clad copper-clad (FR7031, DuPont) is laminated onto a PDMS bed (10:1 Sylgard 184, Dow Corning) with rigid aluminum backing and processed using UV laser micromachining (Protolaser U3, LPKF). The film is cut at a power of 2 W at 135 mm sec^{-1} with 18 repetitions. After processing, the film is cleaned with isopropanol alcohol and the excess copper film is removed and discarded. This method was introduced in [3].

Next, shown in Figure 6b, a thin, compliant thermoplastic polyurethane (TPU) heat-sensitive film (3412, Bemis), cut to the approximate size of the copper traces using a CO_2 laser cutter, is laminated onto the copper traces using a hand-iron or heat press (120° C, 30 secs). The film adhesively bonds to the copper traces and the stack is removed from the PDMS bed.

A pressure-sensitive tape that is conductive through its thickness (ECATT 9703, 3M) is cut into the approximate shape of the IC modules and bonded to the bottom side (Figure 6c). The IC modules are then visually aligned and electrically connected and adhesively bonded to the stretchable copper interconnects using light pressure. Next, as shown in Figure 6d, the electrical circuits are placed within a foam mold (Poron, Rogers Corp.) that is cut to the approximate size of the electronic bandage with cutouts for the larger modules (*e.g.* battery). The spandex blend fabric substrate is cut using a CO_2 laser cutter and adhesively bonded

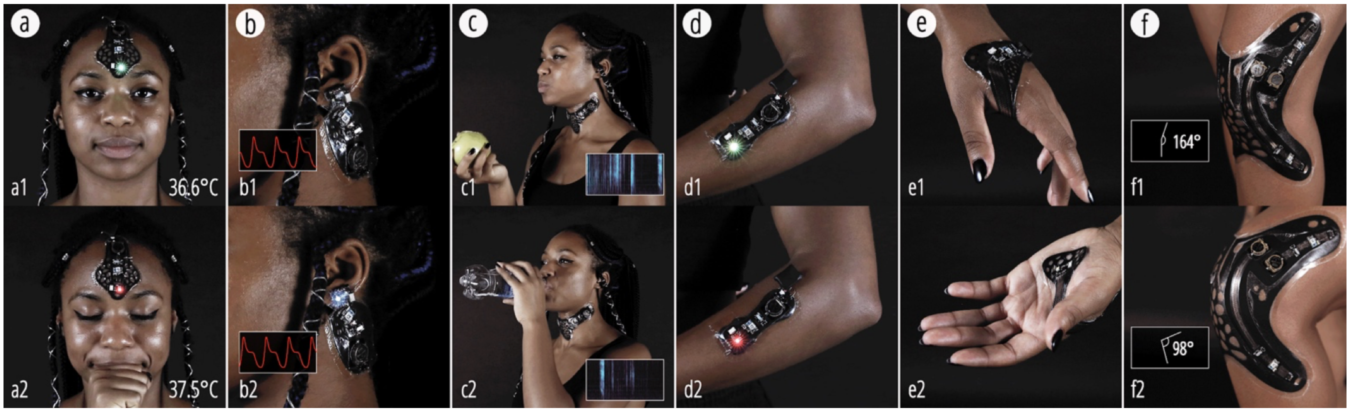

Figure 7: Example applications of ElectroDermis. (a) Forehead temperature sensing mask. (b) Earring for pulse rate detection. (c) Necklace. (d) Smart wound healing bandage. (e) Environment color mirroring jewelry. (f) Motion tracing knee wrap.

to multilayer stack using a heat press (120° C, 60 secs), as shown in Figure 6d.

Finally, a transparent, medical grade adhesive film (Tegaderm, 3M) is cut slightly larger than the size of the electronic bandage with holes for the IC modules using a CO_2 laser cutter. The film is adhesively bonded to the top of the multilayer stack to provide a method for attaching to the body (Figure 6e). The electronic bandage is attached to the body by applying light pressure and peeling of the backing layer (Figure 9a). The medical grade adhesive can be easily removed from the electronic bandage and replaced, allowing the device to be reused (Figure 9d). Within each layer of the electronic bandage, we intentionally follow the shape of the IC modules and copper traces to minimize waste and material consumption. All non-metallic materials, unless otherwise noted, were cut using a CO_2 laser cutter.

5 EXAMPLE APPLICATIONS

We took real-world inspiration from medical bandages — easy to attach, small enough to be unobtrusive, and customized to fit other parts of the body (*e.g.*, bandages for finger tips, noise, etc.). The ultimate objective of the ElectroDermis fabrication system is to provide a design tool and fabrication method to support a process where wearable electronics can be applied to the body from a single, peel-off step, just like a bandage. This method would allow electronics to easily access locations on the body that were previously difficult to access, time consuming to design or even not possible using existing methods. To evaluate the feasibility of this approach, we provide six different electronic bandage applications that are fully functional, each illustrating a different location on the body of varying geometric complexity (*e.g.,* double-curved surfaces) and functionality (*e.g.* health, entertainment, decorative/beauty). All applications require the electronic bandages to be soft and conformal to adhere to the desired body location. Each bandage was created in less than one hour from initial design concept to final device, are small enough to be powered by coin-cell batteries, support wireless communication (*e.g.*, Bluetooth and WiFi), all while being fully untethered (Figure 8).

Figure 8: Our ElectroDermis prototypes pre-worn.

5.1 Forehead and Temperature Mask

Body temperature is one of the four main vital signs and can provide cues about the onset of illness in adults. We created a decorative forehead mask with temperature sensor and RGB LED to provide a simple, non-invasive, and real-time assessment of body temperature (*e.g.*, green: nominal, red: elevated body temperature; Figure 7a).

5.2 Vitals Monitoring

Likewise, another main vital sign is pulse rate. We create an earring that noninvasively monitors pulse rate and blood oxygen saturation (Figure 7b). An LED blinks at the frequency of the wearers pulse rate. This example demonstrates a geometrically complex, non-developable surface on the human body and includes both electronics that face outwards for interaction (LED) and face towards the skin to monitor biosignals (pulse oximeter). The vital monitoring sensor is placed at the end of the bandage and the bandage is folded 180° to allow the sensor to face the skin (Figure 9c). A subset of the photoplethysmogram (PPG) signal that was recorded from the vital monitoring earring is shown in Figure 10a.

5.3 Food Detecting Necklace

Keeping track of daily food intake can provide many benefits and can reveal surprising trends about diet or eating habits. However, this task can be difficult and unreliable, with simply forgetting to journal being the largest barrier [5]. Here, we create a wearable necklace that can classify a variety of foods including potato chips, fruit, and liquids to reduce the largest barrier in food journaling (Figure 7c). The necklace demonstrates a distributed architecture approach and contains two independent electronic circuits to monitor high-fidelity acceleration [17] and sound at the neck.

5.4 Smart Wound Healing Bandage

Chronic skin wounds from burns, diabetes, or other medical conditions can be a significant medical problem. The surrounding skin color can be used as an indication of the healing process, where healthy tissue is typically pink in color while unhealthy tissue ranges from yellow to dark red or black in color [9]. Here we create a smart bandage with a single pixel camera that faces toward the skin to monitor the wound healing process (Figure 7d). A foam wall is placed around the camera to elevate the sensor and prevent it from contacting the skin (Figure 9b). As previously described, the sensor is placed at the end of the bandage and is folded 180° to allow the sensor to face the skin. Based on the healing status of the wound, a RGB LED provides a visual indication of the healing process by fading from red, to yellow, to green.

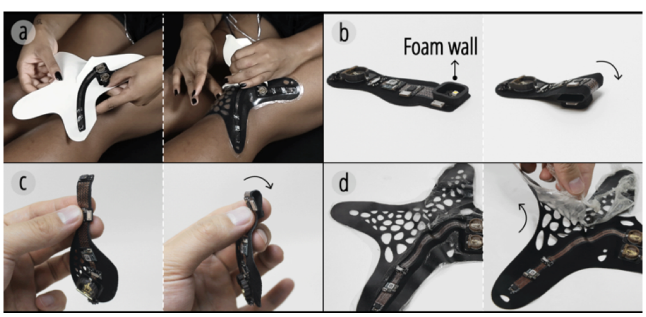

Figure 9: (a) Application of the ElectroDermis. (b) Foam wall used to elevate and prevent the camera from contacting the skin in the smart wound healing bandage. (c) Folding of the vital monitoring earring to allow the pulse oximeter to face the skin. (d) Removal of the skin adhesive for reuse.

5.5 Environment Color Mirroring

Using the previous embodiment, the single pixel camera is faced outwards and is used to explore colors found in everyday materials (Figure 7e). These colors found in the environment are then copied to the body worn jewelry. This example highlights the of ability of the design tool to select a highly complex geometric pattern on the human body and generate a conformal electronic bandage that is intricately routed from the wrist to the palm. This would be an extremely difficult and time intensive task to complete using existing circuit design tools (*e.g.* Altium, Eagle, or KiCad) that primarily provide tools for creating 2D, planar circuits.

Human Motion Tracking

The human body is constantly moving, and most parts are non-planar surfaces — a challenging landscape. For example, an electronic patch on the knee will need well-designed contours to prevent delamination. Tracking articulated human motion is of interest in numerous applications from activity classification, rehabilitation, and biomechatronics [12]. Here, we create an electronic bandage for human motion assessment (Figure 7f). The motion tracking bandage demonstrates a distributed architecture approach and contains two independent electronic circuits to monitor orientation and motion of the proximal and distal shank of the leg. The accelerometers are located directly above and below the knee. The calculated knee angle is shown in Figure 10b. Furthermore, this example highlights the ability of the stretchable electronic bandage to intimately interact with the user without limiting the kinematics or dynamic motion of the human body.

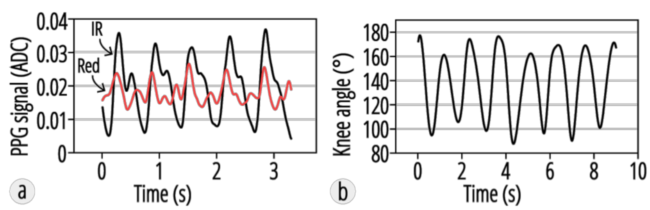

Figure 10: (a) Photoplethysmogram (PPG) signal from the vital monitoring earring. The waveforms can be used to noninvasively measure heart rate and blood oxygenation saturation. (b) Calculated knee angle from the human motion tracking electronic bandage. A low-pass smoothing filtered was applied to both signals.

6 EVALUATION

We characterize the multilayer stretchable electronic circuit under tensile loading to evaluate device performance. The stretchable electrical wiring was first examined by stretching a single electrical interconnect, which is laminated onto fabric substrate using TPU film until failure occurred (electrical or mechanical). The electrical wiring was loaded at a rate of 100 mm min^{-1} and is observed to be soft, highly deformable (maximum elongation: 164.8 ± 10.9%) and exhibit a minimal absolute change in electrical resistance as a function of applied strain (<10% at 170% strain; Figure 11a). A photograph sequence of increasing strain is shown in Figure 11c, where electrical failure occurs shortly after a strain of 171%.

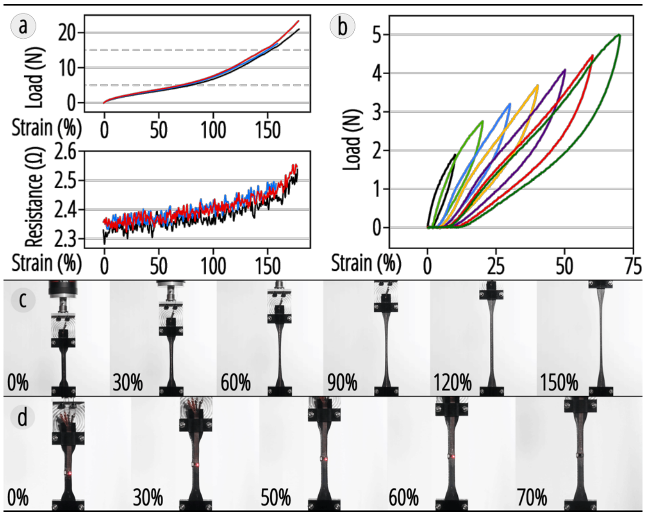

Figure 11: (a) Load and absolute resistance versus strain under uniaxial deformation. (b) Cyclic loading to increasing strains as a function of strain. (c-d) Photograph sequence at increasing levels of strain until electrical failure occurs for the stretchable (c) electrical wiring and (d) serially addressable 4-wire LED device.

Cyclic testing was then completed for the four-wire, serially addressable LED, which was located at the center of a dogbone sample. The device was strained for two cycles at increasing levels of strain from 10%, 20%, 30%, 40%, 50%, 60%, and 70% strain (Figure 11b). A photograph sequence of increasing strain and a magnified image of the electrical trace is shown in Figure 11d. The rigid component introduces a stress concentration and results in premature failure of the device shortly before reaching a strain of 70%. Overall, the device is soft and has a similar elastic modulus (1.3 MPa) to biological tissue, which is important for comfort and compatibility with the human body.

7 LIMITATIONS

Fabrication tool. The ElectroDermis fabrication approach currently requires an advanced laser micromachining system that is capable of processing thin metal films. This type of laser system is limited to fiber or UV based laser systems, which are not readily available in fabrication labs and can be prohibitively expensive. This fabrication approach and the entire wearable electronics community would greatly benefit from an affordable and accessible fabrication tool or process that does not require cleanroom fabrication techniques or expensive fabrication tools that is capable of processing thin metals into complex patterns that are not just flexible but highly stretchable (stain > 100%).

Washability: The current electronic bandages are not sealed and are susceptible to damage from moisture. Future devices will greatly benefit from thin waterproof coatings that would allow the electronic bandage to be machine washable and used in damp or wet environments such as on rainy days or in swimming pools.

Electrical wiring: The current electronic bandages use electrical traces that are patterned from an intrinsically rigid material (copper). To enable the material to be easily deformed, the copper film is patterned into a wavy, serpentine shape, increasing the overall width of the trace and limiting the density of electrical wiring.

Circuit integration: The advanced integrated circuits are integrated into the ElectroDermis fabrication approach using flexible printed circuit boards. While small and flexible, these boards result in inextensible "islands" within the bandage that do not match the mechanical properties of the skin and limit their local placement on the human body.

8 CONCLUSION

In this work, we present ElectroDermis, a holistic fabrication approach to simplify the creation of wearable electronics that achieve high functionality in a stretchable and robust form-factor. Specifically, we achieve high functionality by discretizing rigid print circuit boards into individual islands. There islands are then assembled on a spandex-blend fabric to increase robustness and reusability. ElectroDermis also provides a new design tool and fabrication approach to empower and introduce even novice makers to stretchable, on-skin electronics. Using these tools, we designed six different, highly customizable and functional, wireless electronic bandages, all in under one hour from conception to final product. Furthermore, this design tool enables wavy, serpentine architectures to be parametrically superimposed on complex and curved trajectories. Finally, our examples highlight the versatility and generality of this fabrication approach, and the ability to easily provide access to simple and geometrically complex locations on the human body.

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