BodyPrinter: Fabricating Circuits Directly on the Skin at Arbitrary Locations Using a Wearable Compact Plotter

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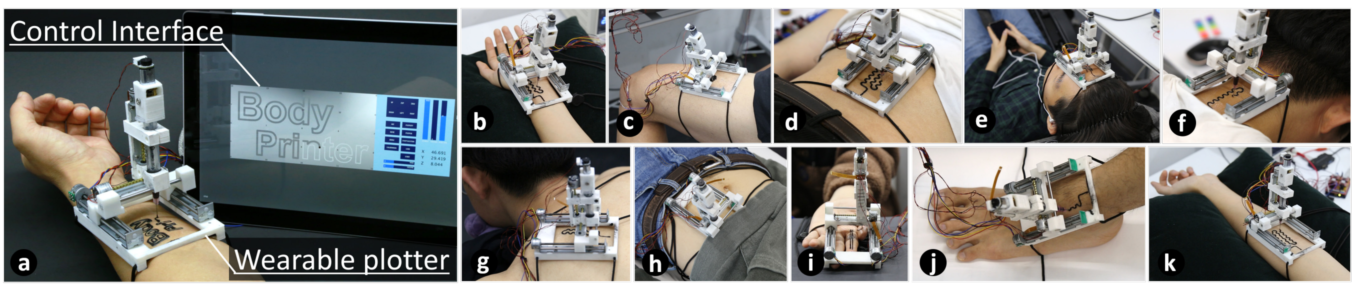


Figure 1. BodyPrinter (a) is a compact wearable plotter that allows printing conductive circuits directly onto the skin in various body locations (b-k).

ABSTRACT
On-body electronics and sensors offer the opportunity to seamlessly augment the human with computing power. Accordingly, numerous previous work investigated methods that exploit conductive materials and flexible substrates to fabricate circuits in the form of wearable devices, stretchable patches, and stickers that can be attached to the skin. For all these methods, the fabrication process involves several manual steps, such as designing the circuit in software, constructing conductive patches, and manually placing these physical patches on the body. In contrast, in this work, we propose to fabricate electronics directly on the skin. We present *BodyPrinter*, a wearable conductive-ink deposition machine, that prints flexible electronics directly on the body using skin-safe conductive ink. The paper describes our system in detail and, through a series of examples and a technical evaluation, we show how direct on-body fabrication of electronic circuits and sensors can further enhance the human body.

UIST'20, October 20–23, 2020, Minneapolis, MN, USA

ISBN 978-1-4503-6708-0/20/04...$15.00

DOI: https://doi.org/10.1145/3313831.XXXXXXX

Author Keywords
On-body fabrication; wearable; skin electronics.

CCS Concepts
•**Human-centered computing** → **Human computer interaction (HCI);**

INTRODUCTION
On-body electronics promises a seamless integration of computers and sensors with our bodies. In human-computer interaction (HCI), on-body electronics has been investigated as a novel interaction medium [16, 27, 28], and researchers developed techniques to make on-body electronic fabrication customizable and accessible [10,18] through careful consideration of various wearability factors [15]. Specifically, a number of research projects have focused on creating stretchable electronics for the skin using metal serpentine interconnects encased in silicone [13], carbon particles [27], and liquid metals [3]. The majority of these techniques follow the same design and fabrication workflow; the electronics are fabricated (manually or mechanically) on planar surfaces as two-dimension stickers or tattoos, and are placed on the body afterward. The fabrication process typically requires multiple steps as conductive materials have to be deposited on a flexible substrate so that it can later be attached to the body. This process is inherently laborious, error-prone, and often handed to professional makeup artists [15], as it usually involves multiple iterations to create stickers and to correctly apply them to fit the body

as desired. More generally, there is a disconnect between the prototype and the circuit's final form, as design and fabrication are executed in a 2D space, whereas the body is inherently a 3D (and irregular) surface.

In contrast, most traditional on-body fabrication techniques such as body silicone molds, costume props, masks, prosthesis, and casts are manually fabricated directly on the body. The fabrication is done on the body, because the human anatomy is incredibly complex and varies from person to person, and an accurate design cannot be prefabricated. However, this manual process is usually not suitable for the fabrication of electronics, as high accuracy and precision are crucial. We, therefore, see an opportunity to bridge this gap, by introducing a novel prototyping machine and a computer-assisted fabrication process of electronic printed directly on the skin. Specifically, this work was inspired by the recent advances in personal fabrication, which enables one to quickly create prototypes using customized fabrication tools such as 3D printers [19,22], laser cutters [20, 21], and user-friendly software.

We introduce *BodyPrinter*, a wearable conductive ink deposition machine that prints flexible electronics directly on the skin. The machine is a custom-designed miniature plotter that straps to the body and can print onto the curved surface underneath. With minimal calibration and no need of external tracking, BodyPrinter can provide a quick and accessible way to fabricate flexible electronics directly on the skin in various body locations. This approach differs from the few previous attempts to print directly on the skin [32], by employing a regular conductive ink instead of simple pigment or special alloys, and by allowing for the first time to users to print onto arbitrary locations of the body, including fingers, arms, back, belly, forehead, neck, laps and shoulders (Figure 1). As an example application, BodyPrinter can easily create a sensor to detect back postures, by printing directly on the shoulders and the back patterns that change resistance based on how they are bent or stretched (Figure 7). While with traditional fabrication methods many trials would have been required to determine the appropriate location, the right resistance, shape, and size of the sensors, with our system users can quickly design, prototype and test alternatives directly on the desired part of the body.

By proposing a system for direct fabrication on the body, we aim to greatly simplify the design and deployment of on-body and wearable electronics, making them more accessible to makers and users at home. In this aspect, 3D printers are not considered a substitution for traditional fabrication methods but rather a complement enabling users to customize products to bypass structural issues in the physical world [17] and address specific needs. Similarly, we envision that on-body electronics printing will not substitute but rather complement existing methods used to efficiently print large quantities of circuits on flexible/stretchable substrates to be applied to the body at later stages. As in previous work [17], on-body printing offers the users the possibility of *consumer-grade fabrication* for tailoring to specific needs and adapting to suit unique body features.

This paper is structured as follows: First, we investigate relevant previous research. Second, we describe the design and decision rationale for the BodyPrinter device. Third, we present some applications that exemplify the feasibility and usefulness of our approach. We then evaluate the mechanical and electrical characteristics of the printed materials on different body parts. Also, we assess the performance of the BodyPrinter prototype in typical printing tasks. Finally, we discuss the limitations and future work.

RELATED WORK

BodyPrinter builds upon works in the domain of interactive on-skin interfaces and on-body fabrication of thin, wearable electronics, both described here in detail.

Interactive on-skin interfaces

Interfacing the human skin with electronics greatly expands the on-body interaction space available to the user. Successful developments of thin, flexible, stretchable electronics has made on-skin wearable interfaces increasingly durable and practical. iSkin [27], for example, is a thin, flexible, and stretchable sensor overlay composed of biocompatible materials. Using capacitive and resistive touch sensing, it can detect two levels of pressure and multiple touch points, demonstrating potential for direct, quick, discreet input for mobile computing. Similarly, PolySense [7, 26] presents several input interfaces and sensors constructed with piezo-resistive kinesiology tape directly attached to the skin. SkinWire [9] demonstrates a wiring approach to connect electronic components placed on the skin, while PhysioSkin [23] shows a DIY prototyping method for fabricating custom multi-modal physiological sensors.

Output modalities such as lights have been integrated into on-skin interfaces as well. Skintillates [16] uses electrical traces and small electronics such as LEDs fabricated on temporary tattoo paper to create various colorful and expressive displays and sensors that flex naturally with the user's skin. DuoSkin [10] uses gold leaf instead of conductive ink as a skin-friendly conductive material for touch sensing and NFC communication. It also demonstrates the integration of thermochromics and small LEDs for fabricating on-skin color changing displays. Also, adding body landmarks into consideration, the authors of SkinMarks [29] presented skin-worn I/O devices for precisely localized input and integrated visual output. SkinMarks is also compatible with strongly curved and elastic body locations.

Aside from stationary interfaces on the skin, dynamic or actively relocating interfaces on the body allow for high flexibility and wide interaction space. Wearable robotics such as Clothbot [6] uses two-wheeled grippers and mechanical legs to climb clothing and soft materials. Similarly, Rovables [2] uses two-sided magnetic wheels to climb clothing, enabling various sensing, input, and actuation interfaces on the body. Movelet [4] uses a different approach, moving along the user's arm with wheels rolling against the skin to provide haptic and positional feedback.

In line with these previous works, BodyPrinter also is capable of creating on-body functional electronics, such as sensors and

LED displays. However, it differs from other approaches in that electronics are printed directly on the skin and at arbitrary body locations.

Fabrication of on-body electronics

Fabrication of on-body electronics typically involves a two-step process: printing on a flexible, planar substrate, followed by its application on the skin. A line of research focuses on creating small, thin electronics that, after printing, can be easily attached to various surfaces including the human body. Kratas et al. [11] used resistive polarity-switching touch sensing technique for creating custom multi-key touch interfaces printed on paper with conductive ink. Kim et al. [14] proposed an inkjet-printed monopole antenna that can be applied to the body for wearable wireless communication. The antenna was backed by an electromagnetic band gap (EBG) ground plane to isolate the human body from a wireless network system. Ziai and colleagues [33] proposed temporary on-skin inkjet-printed passive UHF RFID transfer tag tattoos as a continuous monitoring mechanism for health care and other mission-critical and secure applications.

Alternatively, another line of research explores making electronic circuits with flexible material for better adhesion to the body. Much of early pioneering work in stretchable skin electronics has been done by Rogers Group (e.g., [13]). Most works of Rogers et al. use standard integrated circuit technologies and serpentine patterns to allow stretching. The devices are then encapsulated in silicone. However, electronics are not directly printed on the skin, but instead they are transferred to the skin using a stamping procedure and a liquid bandage as an adhesion layer [31]. More recent advancements show how conventional desktop printers can be used for electronic tattoos [23] such as multi-ink sensors that are stretchable, ultrathin, high resolution, and integrated with a wide variety of materials [12].

All these techniques show examples of how electronics are printed on supporting substrates and then are applied or attached to the body. However, designing and fabricating accurate wearable patches that seamlessly fit to the body remains a challenge because of the irregular and complex structure of the different parts of the human body [1] — all different in shape, size, and form. To tackle this issue researchers (e.g., [32]) have suggested techniques that allow to print electronic circuits and sensors directly on the user's body. This simplifies the process by requiring a single-step fabrication that can account for the irregular geometries of the body (e.g., curvature).

The authors of ExoSkin [5] proposed a hybrid fabrication system for designing and printing digital artifacts directly on the body with air-dry polymer clay. The user can first create a virtual prototype on the arm with the aid of a visualized projected toolpath. The toolpath can later be traced with a handheld extruder to fabricate the physical prototype directly on the body. Applying 3D tracking and computer vision with closed-loop adaptive 3D printing, Zhu and colleagues [32] demonstrated direct ink printing of functional materials (special conductive silver-particle ink with custom viscosity, not available to consumers) on the dorsal side of a moving hand. However, by employing a commercially available delta 3D-printer, the authors were only able to demonstrate their concept by printing on small surfaces that fit into the printer, like the back of the hand. Beyond the HCI field, Jafari et al. [8] explored the usage of on-body fabrication for medical purposes, by filling wounds with curing fluids. Also, popular media has covered stories of repurposed 3D printing machines [25] and robotic arms [24] that print regular tattoos. By using regular ink these devices do not need an additional extrusion apparatus to deal with the larger and time-dependent viscosity of conductive ink.

In summary, despite some notable past attempt of printing electronics directly on the the skin on limited locations of the body [32], on-body fabrication of electronics mainly consists of methods that require two separate steps — printing followed by attachment to the skin. We argue that this process is inherently laborious. BodyPrinter, on the contrary, enables direct skin printing of electronic circuits on arbitrary body locations (head-to-toe) and differently sized (from the small area of fingers, to the large surfaces of the back), providing direct and immediate cues about the target size, position on the body, and orientation.

BODYPRINTER OVERVIEW AND WALKTHROUGH

BodyPrinter is a compact, wearable CNC plotter that is capable of fabricating circuits by extruding non-toxic conductive ink directly onto the uneven surface of the skin. Because of its small form-factor, BodyPrinter can be easily attached via straps onto different locations on the body. With its simple setup, not only is it possible to easily place the printer on large body parts (e.g., shoulders, forehead, belly) which were not accessible by traditional 3D printers [25, 32], but it also simplifies the software. In fact, it does not require tracking body movements during printing to account for changes and irregularities in real-time, as seen in previous work [32].

The typical fabrication workflow of BodyPrinter involves five main steps: 1) circuit design & preparation, 2) calibration, 3) on-body printing & post-processing, and 4) applications & usage (Figure 2). Details of each phase are described below using as example the design of a strain-gauge sensor following a user's perspective.

Circuit design & preparation. The user designs the desired circuit (e.g., a strain gauge sensor) using CAD software, such as Autodesk Fusion 360[1](Figure 2a). After completion, the circuit is converted into a toolpath and exported as 2D G-code. Using BodyPrinter's control interface software, the user then loads the generated G-code which is then visualized as a 2D toolpath. Any necessary additions to the circuit can be implemented directly by drawing using click and drag gestures with a mouse.

Calibration. Similarly to previous work [30], the user can apply liquid bandage (e.g. Nexcare, 3M) on the skin of the desired printing site to insulate the circuit to be printed, providing better skin-safety and improving the adhesion of the printed circuit. Also, this results in longer-lasting printings. Next, the user wears the BodyPrinter plotter and begins a

[1] https://www.autodesk.com/products/fusion-360/overview

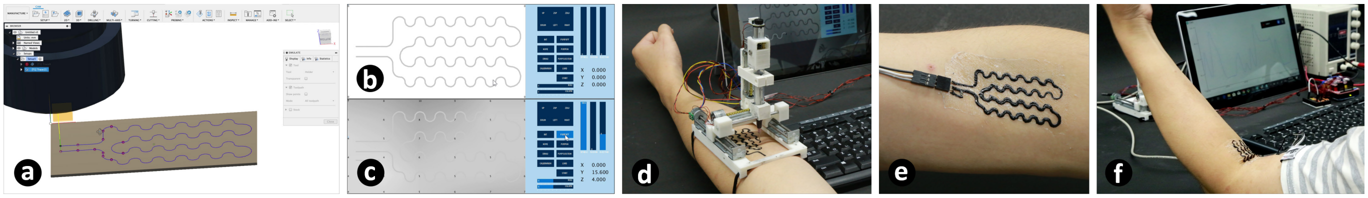


Figure 2. BodyPrinter's workflow. (a) Generating a G-code file. (b) Loading the G-code in the BodyPrinter's software, making changes on the fly, setting parameters, and (c) calibrating. (d) Printing the sensor. (e) Applying other electronic components on the sensor, and (f) demonstrating its usage.

computer-assisted z-axis calibration. After setting the calibration grid resolution, the user proceeds to move the extruder to each calibration point and fine tunes the z-axis value. Once the calibration is completed, the user can adjust the extruder settings to control the thickness of the printed traces. The control interface incorporates the z-axis data into the imported 2D G-code, and converts it into a 3D toolpath that is sent to the hardware control unit.

On-body printing & post-processing. Pressing the "print" button in the control interface begins printing the circuit. The extruder moves along the curvature of the skin according to the 3D toolpath previously generated. Because the plotter is fixed relative to the body, small movements during printing do not affect the printed circuit quality. After the printing is completed, the user removes the plotter and can prepare wiring the circuit with necessary components. The printed circuit typically dries in under ten minutes, and while drying, necessary electronic components are attached directly to the circuit. In the example case presented in Figure 2, a resistor is attached to form a voltage divider on a printed strain gauge sensor. Jumper wires are attached to the ends of the circuits using tape for firm attachment onto the skin. Once the circuit dries, an additional layer of liquid bandage is applied to further insulate the circuit and increase its durability.

Applications & usage. The strain gauge sensor is first wired to an Arduino Uno board that connects to a PC via a serial port. The user can check the input resistance values that change with arm-bending and can design appropriate applications using it. After some tweaking of sensor threshold values in the PC, the sensor and Arduino can be connected to a small battery pack to make a wearable fitness counter for keeping track of arm exercise repetitions.

IMPLEMENTATION

The BodyPrinter system has two main parts. The first part consists of the hardware, which includes a three degrees-of-freedom wearable plotter, a conductive ink extruder, and a motion control unit. The second part is the software which consists of an interface that interprets G-code, performs the calibration of the z-axis, and constructs a 3D toolpath that merges the G-code information with the z-axis information. This new toolpath represents the motion of the ink extruder over the uneven skin surface. The hardware and software communicate through serial port via an Arduino. Design files and software are open-source and available on Github[2].

Hardware and Firmware

The hardware (Figure 3) is composed of a custom 3D printed Cartesian plotter structure with a movable head and an ink extruder mounted on it. The wearable plotter has a total of four bi-polar stepper motors. Two stepper motors (ϕ25 X 15 mm, 18 degrees step angle, operating at 8 V and 500 mA) each with a threaded rod (ϕ3 x 90 mm, 0.5 mm pitch) are mounted on the opposite edges of the 3D printed base of the plotter, moving the extruder in the x-axis. Two additional steppers (ϕ15 x 12 mm, operating at 5 V with 200 mA) and their relative threaded rods (ϕ3 x 53 mm, 2mm pitch) are mounted on additional 3D supporting structures and allow extruder movement in the y and z (vertical) axes respectively. The maximum resolution of motion on the xy plane is 0.3 mm, and the maximum speed is 8.3 mm/s. The resolution on the z-axis is 0.1 mm.

The conductive ink extruder is mounted on the plotter's head. It is made of a syringe and a geared DC motor (gear ratio: 1:298, torque: 1.1 kg/cm at 40 rpm, operating at 8 V and 140 mA) with a threaded rod(ϕ3 x 90 mm, pitch: 0.5 mm) used to extrude the ink. The syringe has a 3D printed plunger attached to a nut (pitch: 0.5 mm), and it is connected to the threaded rod driven by the motor. The nozzle size of the syringe is ϕ0.5 mm, from which the ink contained in the barrel of the syringe is extruded. The barrel contains up to 1.5 mL of commercially available, skin-safe, conductive ink[3]. Alternate ink options such as silver nano-particles and conductive paste[4] were not

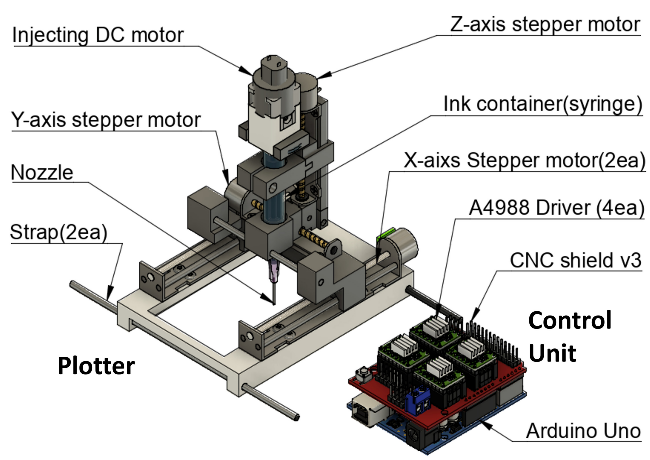


Figure 3. Isometric view of BodyPrinter structure and its parts.

[2] https://github.com/makinteractlab/BodyPrinter

[3] https://www.bareconductive.com

[4] https://pubchem.ncbi.nlm.nih.gov/substance/329765060

used considering skin-safety, following the manufacturer's recommendation (i.e., GHS07, GHS08). The syringe is housed in a 3D printed holster attached to the movable plotter head of BodyPrinter. All parts of the structure and the extruder were 3D printed in PolyLactic Acid (PLA), and the overall plotter dimensions are 120 x 80 x 140 mm with a printing area of 74 x 39 mm.

The electronic control unit includes an Arduino Uno microcontroller, a CNC Arduino shield V3 with four A4988 stepper motor drivers, and one L293D H-bridge integrated circuit. The entire system is powered through an 8 V DC power supply. The Arduino Uno runs the GRBL[5] open-source CNC software, and it is used to control extruder location with corresponding motor movements. Specifically, the two steppers placed along the x-axis are synchronized such as to avoid any structural twisting along the y-axis. The H-bridge chip is located on a separate breadboard (45 mm x 35 mm), and it controls the depth and direction of motion of the plunger on the extruder. Normally the plunger is pushed to eject ink, but it can also be pulled when the syringe needs to be refilled or when there are intentional gaps in the circuit.

Software

The BodyPrinter software is written in Java and runs on PC. It consists of: 1) a graphical interface displaying the circuit toolpath to print as well as general control settings, and 2) a control algorithm.

The graphical interface (Figure 4.a) displays the circuit corresponding to the G-code commands loaded by the software. It also allows the users to draw custom shapes that can be printed together. The interface shows the numerical value for the z-axis displayed as a grid overlay over the toolpath. The right side of the screen contains a control panel with buttons and sliders (Figure 4.b). This panel ultimately allows the users to precisely control the behavior of the machine, such as moving the nozzle in any of the three axes; initializing, calibrating, and starting the printing; vertically moving the plunger of the syringe to either refill the syringe or extrude ink; and setting the thickness of the printed circuit. For example, setting the plunger at maximum force (100% duty-cycle) would ensure that lines are printed with an approximate thickness of 2 mm.

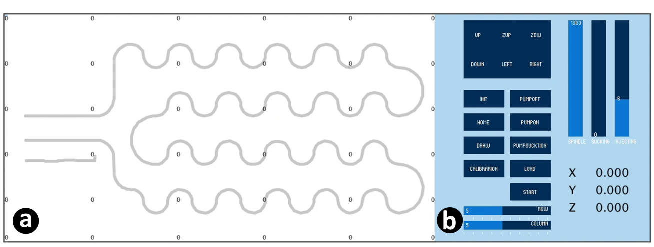


Figure 4. Graphical interface for BodyPrinter's (a) calibration procedure , and (b) settings.

Through the calibration process, the system is capable of inferring the shape of the printing surface given a limited set of calibration points. The calibration points result from subdividing the printing area into a desired number of rows and columns between 6 and 11, depending on the complexity of the body part to be printed on. The equidistant vertices resulting from this subdivision constitute the calibration points. Thus the system supports a minimum calibration grid of 36 vertices and a maximum of 121 vertices. At maximum resolution, calibration points are 6.7 mm and 3.6 mm apart in the x and y directions respectively. Any points within the area delimited by four of these vertices (Q_{11} to Q_{22}) can be computed with the formula in Figure 5, which shows a bilinear interpolation of the height of the traces f at the points (x, y). Finally, the algorithm uses the height at each vertex combined with the 2D G-code information to synthetically construct a new path in 3D, which contains the coordinates of the circuit with height values of the body surface. The new set of G-code commands are fed into the Arduino and used to control the location of the extruder in the three axes.

To perform the calibration, at each point the user needs to manually adjust the vertical height of the extruder in small increments until it touches the skin - a process very similar to that used in CNC milling machines. Only the points in close proximity to the circuit require calibration. During calibration, the extruder can be moved with a precision of 0.1 mm and with a speed of 8.3 mm/s. For relatively flat body parts, it is sufficient to use 6x6 points for calibration, which takes less than 5 minutes to complete.

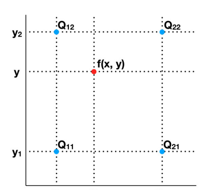
EXAMPLE APPLICATIONS

The following section presents several applications that exemplify how BodyPrinter is used to create circuits directly onto the skin of different body parts. In these examples we specifically chose body parts that cannot be printed using customized commercially available 3D printers and thus traditionally require designers to prefabricate circuits on substrates (e.g., stickers) and subsequently apply them onto the skin. BodyPrinter, in contrast, achieves this in a single step.

All circuit paths from the examples were generated with Autodesk Fusion 360 and exported in G-code. Calibrations were performed once per application using 36 vertices (6 rows x 6 columns), except for the finger input controller that used 121 vertices (11x11). Calibrations took between 1 and 5 minutes, and printing took 3.5 minutes on average.

1. Sensing motion and postures

Printing strain gauge sensors directly on the body enables direct measurements of the strain applied to the skin at particular locations. In fact, the printed circuit deforms with the skin and allows to estimate the intensity of the deformation through the varying resistance sensed by an Analog-to-Digital Converter



$$f(x,y) = \frac{1}{(x_2-x_1)(y_2-y_1)} \begin{vmatrix} x_2-x & x-x_1 \end{vmatrix} \times \begin{vmatrix} f(Q_{11}) & f(Q_{12}) \\ f(Q_{21}) & f(Q_{22}) \end{vmatrix} \begin{vmatrix} y_2-y \\ y-y_1 \end{vmatrix}$$

Figure 5. The four blue dots show the data points, the red dot is the point where we want to interpolate.

[5] https://github.com/grbl/grbl/wiki

(ADC). It is therefore possible to detect motion, postures, and various types of input gestures in real-time. As mentioned in the walkthrough, we designed and tested strain gauge sensors with a serpentine pattern (20 kΩ) to which we attached a 20 kΩ SMD resistor (3216 sizes) to compose a voltage divider.

With this setup we printed two strain gauge sensors to track the movements of an arm (Figure 6). We placed the sensors on the wrist and elbow pit, then took the resistance data from the analog pins of an Arduino Uno, applied a low-pass filter in software for stabilization, and mapped the values to the rotation angles of the joints to a simplified skeleton model. A graphical user interface written in Java renders on screen the movements of the arm in real-time.

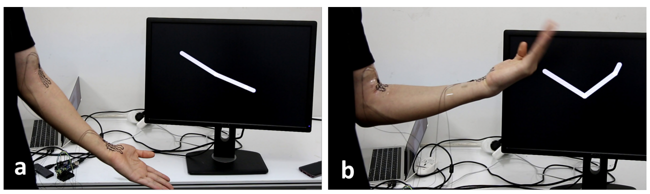


Figure 6. The readings from two strain gauge sensors placed on the wrist and elbow pit are mapped to the joints' angles of a digital skeleton arm.

Similarly, in another application we used two strain gauge sensors to detect the quality of the user's sitting posture (Figure 7). The sensors are printed on the upper and lower part of the back, and their combined readings are used to infer the user's posture and provide visual feedback to the user. This application demonstrates that BodyPrinter can be used for circuits placed on large areas (e.g., back and shoulders) that cannot be possibly reached with traditional printers. It also shows how sensors can be covered by clothes without creating any interference.

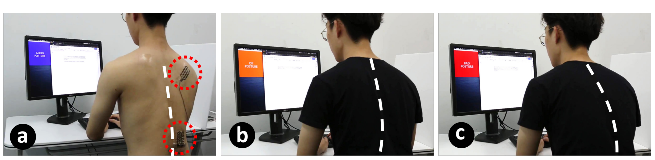


Figure 7. A pair of strain gauge sensors placed on the back are used to sense good (a), moderate (b), and bad (c) postures.

2. Sensing body capacitance

By sensing body capacitance it is possible to detect contact with other people, and to determine the user's activity, such as standing, walking, and jumping barefoot (Figure 8). We note that when the contact area between the user and ground decreases, the body capacitance decreased accordingly. When instead the user touches other people, the relative capacitance increases. We used these observations for creating the two simple applications shown in Figure 8. The first application shows the reliable detection of touches from different people. The second application shows the detection of movements such as standing, walking, and jumping.

To measure the capacitance we measured with an Arduino the time needed to charge the capacitor (i.e., RT constant) using the CapactiveSensor library[6] and the known 1 MΩ resistance of the printed sensor. Following these example applications, it is easy to envision other opportunities for this type of sensing, including step counters, fitness trackers, or other type of single/multi-user activity recognition.

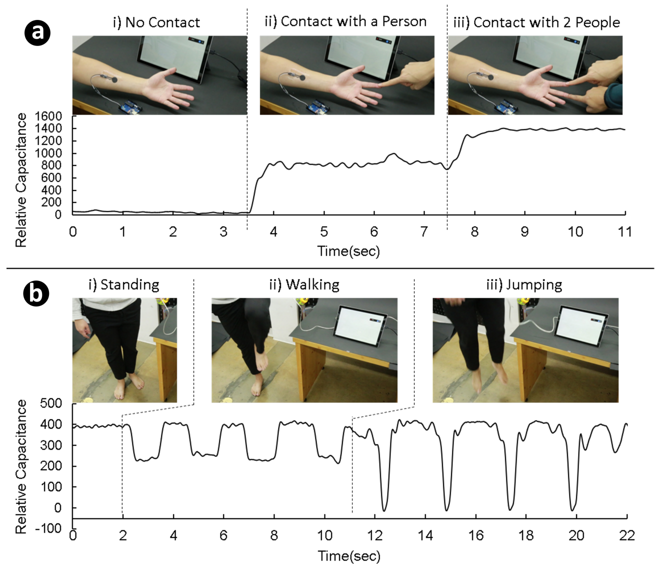


Figure 8. Relative capacitance changes as multiple people touch user (a), and as the user's movements (b).

3. On-body input gestures

On-body circuits can be configured for detecting different input gestures mapped to control specific interfaces. Using the notion of a voltage divider we printed a slider controller directly onto the user's fingers. Two parallel lines (up to 20 kΩ) run across the index finger, while a circle-shaped switch is printed on the thumb. When the thumb touches the rails of the slider it effectively closes the circuit, allowing an Arduino to sense the corresponding resistance between the beginning of the slider and the location where the touch occurred. We then mapped this value to the volume level of a music player (Figure 9). This application demonstrates that BodyPrinter can print on small and curved surfaces of the body, such as the fingers. Furthermore, it shows that direct printing can reduce the overall fabrication time. In fact, we did not need two separate fabrication stages for the slider and switch, because we printed them all together at once (Figure 1.i).

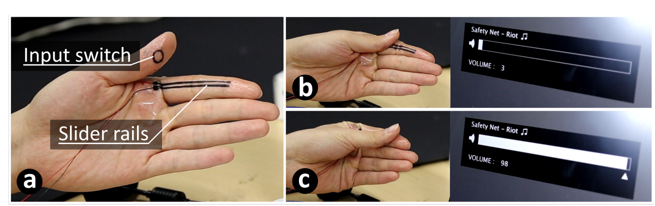


Figure 9. (a) A media volume controller printed on the finger. (b-c) Closing the circuit with the thumb on the different parts of the index finger results in changes of the output volume level.

[6] https://www.arduinolibraries.info/libraries/capacitive-sensor

In the second application, we repurposed a strain gauge sensor for detecting a variety of input gestures, such as bending, twisting and squeezing. Figure 10 shows how resistance dramatically changes with the bending, twisting, and squeezing input actions. Although not explored in this paper, it is easy to conceive subtle input gestures that could be mapped with various commands — such as snoozing an alarm or silencing a phone. The reliability of the bending gesture also suggests the potential for fitness tracking applications, such as counting the number of repetition while weight-training.

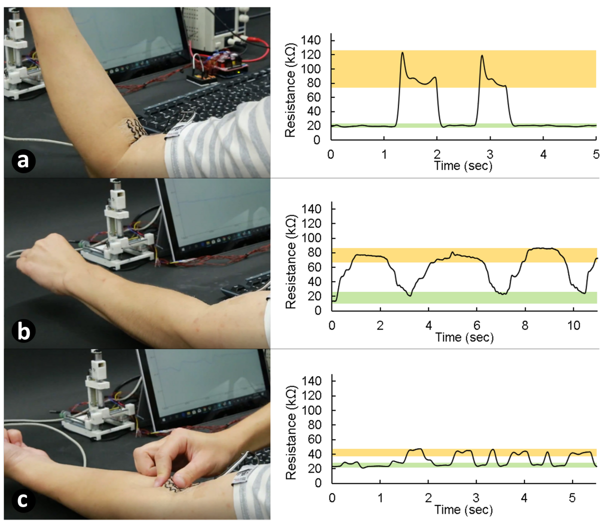


Figure 10. The images of 3 input postures (bending (a), twisting (b), squeezing (c)) and their measured resistance over time. The range of resistance for the idle and input postures are highlighted in green and yellow respectively.

4. LED displays

Using BodyPrinter it is possible to make LED displays that are both functional and aesthetically pleasing. Figure 11.b shows a tattoo of flames printed on the forehead, with six red LEDs for creating an animation effect. LEDs are controlled individually using charlieplexing, which allows up to eight LEDs to be controlled with only three wires connected to an Arduino. On the left side, we show more examples of LED displays printed on the forearms. As for previous applications, we note that BodyPrinter support printing on body parts, like the forehead, that are typically not accessible or safe for printing with conventional 3D printers.

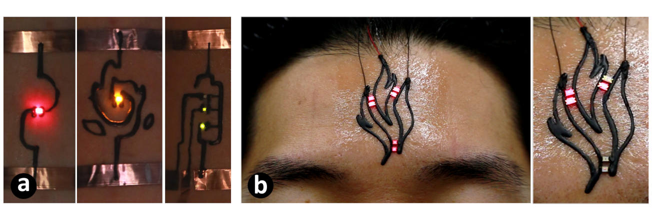


Figure 11. Various examples of LED displays printed on the arms (a) and on the forehead (b). The latter shows a charlieplexing configuration, with six LEDs individually controlled using only three wires.

TECHNICAL EVALUATION

We conducted a set of tests to evaluate the electrical characteristics and durability of the printed circuits, and to verify the performance of the device as a fabrication tool (e.g., printing and calibration time). The first group of tests was performed by printing on flat sheets of paper. The results provide a baseline condition and were used to determine a suitable extrusion rate, and to characterize how resistance varies according to different trace lengths and time. The second group of tests required printing directly on the skin. We aimed to verify whether the behavior of the conductive ink changed from paper, and we further collected parameters that describe the performance of printing on different body parts.

Extrusion rate and resistance/length relationship

Printing on paper provides a convenient baseline performance to inspect how the resistivity of the ink change depending on the extrusion rate, drying time and traces length. To standardize the behavior of BodyPrinter, we set our extrusion rate to operate at 100% duty cycle, with the motor activating intermittently for burst of 0.2 seconds over a varying length. Empirically, we conveniently define our extrusion rate unit as one E, meaning one extruding burst over a length of 3 mm. Consequently, smaller extrusions rates are represented by fractions, with $E/2$ indicating an extrusion spread over a trace of 6 mm, $E/3$ over 9mm, and so on.

To understand the basic ink characteristics over time, we printed on a flat sheet of paper five parallel straight lines with five extrusion rates (E, $E/2$, $E/3$, $E/4$, $E/5$). With a total of 25 lines, we collected measured data for resistance using a Keysight U1733C LCR meter for every 5 minutes after printing until 30 minutes, and then for every 10 minutes until 60 minutes. In addition, we measured the actual length and width of the drawn traces using a vernier caliper to test for consistency. Results are shown in Table 1 and Figure 12.

Traces resistance and physical characteristics greatly vary depending on the extrusion rate. In fact, extrusion rates affect both the thickness of the traces and the duration of the drying time, potentially causing inconsistent measurements. Typically, high extrusion rates (e.g., E, E/2) form tick traces that take long to dry off and with high resistance levels (in the order of hundreds of kilo-ohms). Furthermore, the rate of change of resistance, as a function of time, is also very steep (e.g., from 150 $k\Omega$ to 0.52 $k\Omega$ for 1E, and from 16.62 $k\Omega$ to 0.69 $k\Omega$ for E/2), causing too much variability in the circuit. We concluded that E/3 offers the best trade-off, as it results in thin consistent traces (1.3-2.4 mm) that can dry within short amount of time (10 minutes), and with a relatively small variation of resistance over time (few kilo-ohms).

To understand how resistance varies in relation to the length of the traces, we printed 7 additional sets of 5 parallel straight lines on paper using an extrusion rate of E/3. Lines were printed with different lengths in the range 10-70 mm, with 10mm increments. After a drying period of 10 minutes, we measured the resistance of the 35 traces. Results show that resistance is linearly proportional to the trace length and its growth rage is approximately 114.3 Ω/mm (Figure 12). These combined findings support our choice for extrusion rate, and characterize the linear behavior of dried ink for varying lengths.

Extrusion Rate	R_{10min} ($k\Omega$)	R_{60min} ($k\Omega$)	*width* (*mm*)	*length* (*mm*)
E	150.00 (9.51)	0.52 (0.01)	1.6 - 2.5	36.76 (0.11)
E/2	16.62 (4.58)	0.69 (0.09)	1.7 - 2.4	36.04 (0.09)
E/3	3.30 (0.30)	1.09 (0.21)	1.3 - 2.4	36.00 (0.10)
E/4	4.71 (0.26)	1.31 (0.14)	1.1 - 2.0	35.90 (0.07)
E/5	10.90 (1.41)	9.26 (1.36)	1.1 - 1.8	35.70 (0.12)

Table 1. Electrical and physical characteristics of traces printed with different extrusion rates.

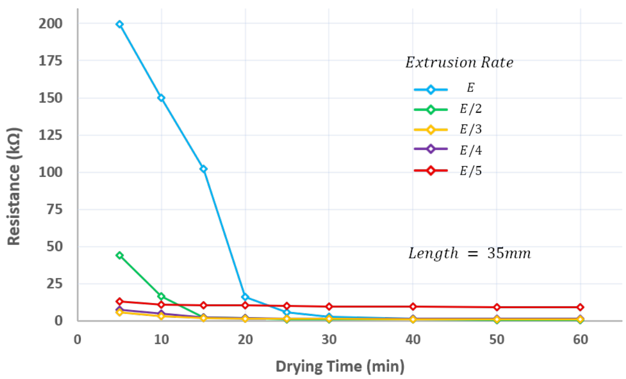


Figure 12. A resistance-drying time graph of traces printed with various extrusion rates.

Traces on the body

The second half of the technical evaluation focused on printing directly on the body of one of the authors. To start we replicated the last experiment from the previous subsection: we printed on the volar side of the forearm 7 sets of five parallel straight lines using seven different lengths (in the range 10-70 mm). As before, after 10 minutes drying time we measured the resistance. Figure 13 shows the results and reveals an almost identical behavior of the traces printed on the body compared with those on paper. For the body we report a growth rate of 112.8 Ω/mm (a difference from paper of about 1%). We further analyzed with a Chow test the two linear regressions formed by the resistance data collected on the two substrates (paper vs. skin) and found no statistical differences ($F = 0.2066, p = 0.81$). We conclude that traces printed on body follow a linear behavior identical to that on paper.

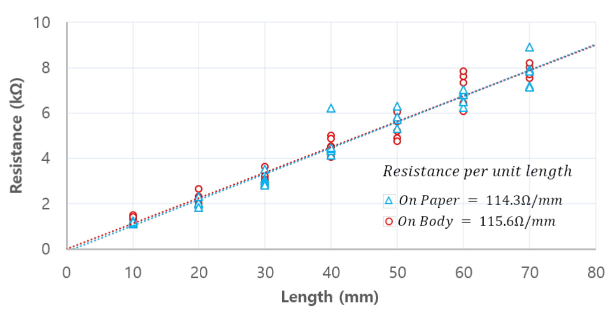


Figure 13. Resistance-length time graph traces printed with different extrusion rates.

Finally, we explored the feasibility of printing on eight different body parts with various curvature, and report on both the traces' electrical characteristics, calibration and printing time. With E/3 extrusion rate, we printed two parallel line of length 35 mm for all body locations except the index finger, where, because of the limited surface area and high curvature, we printed two traces of length 10 mm. As before, after 10 minutes we measured electrical and physical characteristics of the traces. Table 6.2 shows consistent data for the width, length, resistance, and curvature (κ) of the printed lines. This data shows that it is possible to print on surfaces with various curvature, up to a tested 0.121 mm^{-1}. Finally we report the calibration time t_c and the printing time t_p necessary for fabrication. On average calibration took 138.8, (SD:21.9) seconds, while printing took 100.0 (SD: 26.6) seconds. Lastly, we tested the durability of traces against external deformation. We printed a strain gauge sensor (similar to those in the application section) on the elbow pit, measured the trace resistance, and repeatedly fully bent and fully extended the arm in the same manner 1000 times. We then measured again the trace resistance for changes. Resistance decreased of 7%, suggesting that the stretch sensor is usable for over 1000 inputs.

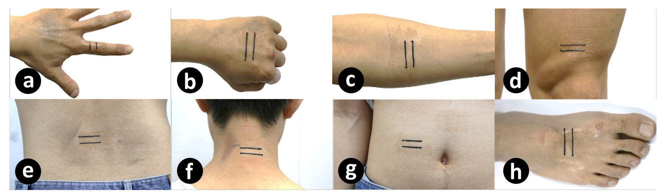


Figure 14. A pair of fabricated wires on various body parts: (a) index finger, (b) back of hand, (c) forearm, (d) thigh, (e) back, (f) back of neck, (g) belly, and (h) foot.

Parts	*width* (*mm*)	*length* (*mm*)	*R* ($k\Omega$)	κ (mm^{-1})	t_p / t_c (*sec*)
finger a	1.5 - 2.4	12.3	1.17	0.121	37 / 90
hand b	1.5 - 2.1	38.5	3.38	0.029	109 / 136
forearm c	1.7 - 2.4	38.0	3.51	0.020	99 / 134
thigh d	1.7 - 2.4	37.8	3.42	0.015	103 / 144
back e	1.7 - 2.2	35.0	3.74	0.013	121 / 152
neck f	1.7 - 2.4	37.8	3.90	0.023	118 / 144
belly g	1.4 - 2.3	35.8	3.11	0.015	112 / 145
foot h	1.6 - 2.3	37.3	3.82	0.026	100 / 165

Table 2. Measurements for width, actual length, resistance, surface curvature and time (calibration/printing).

LIMITATIONS AND FUTURE WORK

Although we worked to make fabrication of circuits with BodyPrinter quick and easy to produce, our prototype system still has several limitations. First of all, it mostly requires a G-code input file that is generated from external software. This problem is partially mitigated by our software support of direct drawing of circuits, but its functionality is limited. Moreover, our prototype requires calibration each time the plotter-hardware is relocated on the body. This task is time-consuming and is probably the most cumbersome step of the printing process. In addition, the post-fabrication process, such as attaching components on the skin before the ink fully dries, requires manual intervention that can potentially introduce errors (e.g., wrong component placement, short circuits, ink expansion due to applied pressure). This manual labor hinders the possibility of production at scale. Following similar related work [5], our future implementation will be integrating a full pipeline in the system so that even novice users could fabricate circuits without complicated steps. We will focus on adding an automatic calibration system with a sensor or a camera that can measure the distance from the surface of the skin (e.g.,to provide a closed-loop feedback). We ultimately envision a complete system with which designers will not only be able to directly print circuits on the body but also design them directly on the body parts of interest, using different materials. Future work is needed to accomplish this vision. Furthermore, future work will consider different usages for on-body fabrication, such as dynamically adaptive fabrication — for example, the BodyPrinter could operate to avoid wounds and bandages, or respond to different jewelry, clothing, body types.

BodyPrinter dispenses conductive ink by actuating the DC motor mounted on the plunger of the syringe. It also has features to adjust the amount of ink injected. However, it is still difficult for users to control the exact amount of ink required for fabricating circuits with even thickness because the properties of conductive ink are prone to changes according to environmental circumstance. In fact, conductive ink traces can result in poor conductivity if dried non-uniformly or even break if not applied adequately. Furthermore, the conductive ink used in our prototype changes viscosity when exposed to air, introducing noise (e.g., bubbles) as a result. Future work is needed to address these practical limitations, perhaps by enclosing the structure to minimize contact with the outside environment or by testing alternative types of inks in conjunction with alternative deposition methods (e.g., brushes instead of dispensing tips). Future work will attempt to validate the feasibility of printing circuits in different parts of the body, considering their durability in respect to different attachment techniques and the flexibility of the body part of interest. Finally, we also plan to evaluate the overall system's user experience through workshops and hands-on sessions with circuit makers or wearable interface designers, considering various skin interfaces and wearability factors [15].

CONCLUSIONS

The potential of circuits and interfaces on the skin has already been demonstrated in several prior works. However, there are currently no tools for quickly fabricating electronics directly on the skin in arbitrary body locations. Most of past works [7, 10, 12, 23, 26] rely on two-steps fabrication, which requires printing on flat substrates such as patches and stickers before being applied to the body. This method does not well account for the body's irregularities and curved surfaces. Alternatively, few works in literature [8, 32] and in the media [24, 25] have shown the potential of directly printing on the users' body, but these examples are strongly limited by the type of ink used (e.g., non-conductive ink [25] or custom-made functional material [32]) and the form-factor of the printing devices which only allow printing on limited locations on the human body (e.g., the dorsal side of the hand). In contrast, we presented BodyPrinter, an on-body fabrication tool for printing electronics with commonly available conductive ink directly on the uneven skin of arbitrary body locations, such as the forehead, arms, fingers, thighs, legs, feet, shoulders, neck, back, and belly. We achieved this by creating a wearable 3D-axis plotter with an ink extruder that is mounted directly on a desired part of the body, requiring only minimal calibration and no tracking for printing. In this paper, we presented the feasibility of the idea, several applications that showcase the potential advantages of this prototyping method, and a preliminary technical evaluation. Our results suggest that this method could be applied for personal fabrication of electronics printed on the body with potential repercussions on fields such as health, HCI, and fashion. Finally, we believe that BodyPrinter could be miniaturized into a small wearable robot to seamlessly and autonomously add stretchable electronics anywhere on the body.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1A2C1012233).

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