SleekPatch: Fabrication of a self-contained, slim hand wearable for interactions in mobile computing

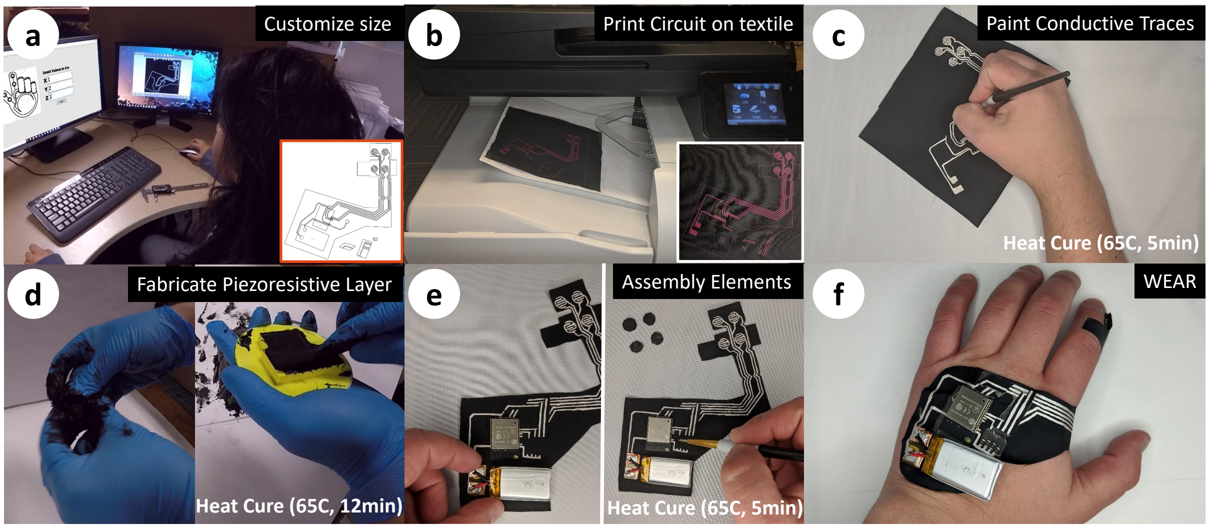

Fig. 1. a) User configuring the size of the wearable, b) Printing template on fabric, c) Painting circuit with conductive ink, d) Mixing elements and fabricating piezoresistive layer, e) Placing electronic elements, f) User wearing his personalized hand wearable

In recent years, hand wearables have gained popularity in applications related to human-computer interaction (HCI). However, these wearables present serious concerns due to bulky form factors and complicated fabrication processes. These concerns limit usability and social acceptance of wearables. We present SleekPatch, a fabrication-workflow that enables the development of a self-contained and slim hand wearable that provides comfort, social acceptance, and mobility to facilitate interactions with mobile computing. We propose a new fabrication workflow for SleekPatch, by combining off-the-shelf textile and conductive inks to generate circuits, instead of complicated, tedious methods such as soldering, sewing, or stitching. We take measurements from the user's phalanges of the index finger and input them into a simple interface to reconfigure a predesigned template of SleekPatch and its sensory input locations. The workflow results in a printable and wearable template for fabrication using conductive ink and off-the-shelf materials. We evaluate technical parameters of fabrication, wearability, slim design, comfort, and applicability with user studies and use cases.

CCS Concepts: • **Human-centered computing** → **Interaction devices**.

Additional Key Words and Phrases: datasets, neural networks, gaze detection, text tagging

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1 INTRODUCTION

Advancements in mobile computing have enabled new types of interfaces and interactions. Recent works have shown unique modes of interaction in mobile computing using wearables in the form of gloves [14], rings [58], adhesives [49, 70], and tracking systems [21] are possible. The diversity in wearables has enabled researchers to investigate a wide variety of interactions such as touch [74], midair gestures [6], and bending [57]. However, providing a wearable that is self-contained, slim, and comfortable to wear is difficult to achieve for three reasons: 1) Integrating hardware is cumbersome due to the incompatibility of components and requires complicated apparatus for fabrication [7], 2) limited space available to distribute electronic components on the hand [10], and 3) The versatility and the large degree of freedom (27) [16] that hands possess, making it difficult to design targeting comfort. To address the above, we propose a design and a fabrication workflow that provides a comfortable yet, socially acceptable hand wearable.

Three main methods have been studied in order to enable the fabrication of interactive hand wearables for users: 1) modifying off-the-shelf gloves by embedding components and sensors with rigid printed circuit boards (PCB) [74, 82], 2) gloves fabricated using stitching and sewing techniques to embed circuits within the glove [19], and 3) polymer-based and transfer paper for adhesive stretchable wearables [9, 32]. For example, we have observed stretchable wearables design and fabrication techniques that allow users to create their own wearables using predefined electronic elements and laser cutting cooper stretchable conductive copper traces [43], and others [26] suggest the combination of a tattoo layer with stitching techniques for interconnecting electronic elements distributed around the body. However, to design a specific wearable for the hand requires additional features that differ from one user to another, such as phalanges measurements or palm-size. Therefore, it becomes cumbersome to create and use a one fits all design for every user. Our proposed workflow considers a design that maintains the location of various components for different users, which benefits comfort while interacting with mobile computing.

We present SleekPatch, a robust fabrication workflow for a self-contained and slim hand wearable, that caters to the varying sizes of hands, provides comfort, social acceptability, and enables unobtrusive interactions with mobile computing.

We use an open form factor that benefits the design and fabrication of the circuit. The geometry is fabricated with a 2D pattern, which enables the placement of circuits on the surface of any material, including objects with fast-changing and complicated surface contours such as hands, without any damage to the circuit. The electronics are distributed over the hand ensuring a slimmer design of the wearable while protecting connections, improving interactions and maintaining the thickness. The wearable is implemented with textiles as substrate, conductive inks for circuitry, and touch piezoresistive as input for interaction. The implemented form factor also enables users to wear SleekPatch under other layers such as protective gloves, which makes it suitable for different work environments such as factories, or laboratories.

To achieve this fabrication workflow, we explored a combination of conductive inks with non-woven textiles, that can enable a robust product while maintaining a small and thin form factor. We determined the compatibility and durability of different circuit traces by combining and comparing several commercially available unisex textiles and conductive inks. To analyze the compatibility, we use a destructive testing approach on the samples of textiles and ink. After the compatibility test, we evaluate the behaviour in a pressure sensor configuration [9]. We also evaluated user preferences on the wearable with different thicknesses for the piezoresistive input modality.

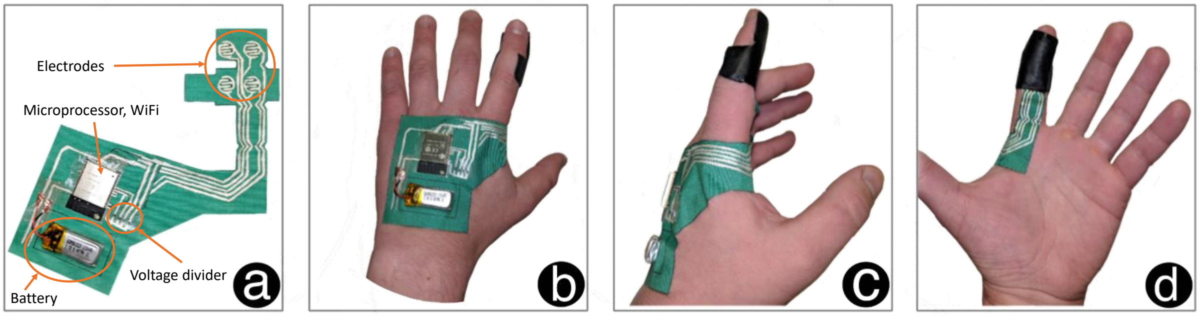

Fig. 2. SleekPatch hand wearable view. a) Hand wearable design printed and painted circuit on fabric, and flat on a surface b) Top view of a hand wearing SleekPatch, c) side view of SleekPatch on hand, d) Palm view of SleekPatch on the hand.

We validated the fabrication, usability, and applicability by performing studies focused on wearability, durability, and social acceptability. Finally, we developed technical use cases to demonstrate the approach.

The following are the contributions of this work:

(1) A fabrication pipeline that enables the creation of a robust, self-contained, small and thin hand wearable that does not require complex fabrication methods or tools and adapts to fit any hand (size and shape).
(2) A material characterization of non-woven off-the-shelf textiles and conductive inks to benefit the fabricability, interactivity, and durability of the wearable.
(3) A set of empirical evaluations of SleekPatch on the users, and three technical applications to validate our design process and applicability in different environments.

The following sections describe related work and technical details that enable the creation of this interactive hand e-wearable.

2 RELATED WORK

2.1 Fabrication of Hand Wearables

The creation of fully integrated electronic hand wearable devices is complicated, due to a large number of degrees of freedom and shapes that a hand possess among different users. Currently, conventional fabrication methods for interactive hand wearables combine stitching, sewing, and knitting with conductive yarns, threads, and soft stretchable materials to achieve the creation of clothing and accessories [7, 20, 46, 47]. A popular approach to create an accessible hand wearable involves the use of tattoo paper as a substrate and bonding agent. The use of tattoo paper creates fast wearables that can enable touch, bend, squeeze interfaces and displays, that can be aesthetically modified, and worn on the body [28, 40, 49, 69, 71]. However, the lifetime of such wearables on the skin is limited to hours and depends on the activity involved. For reducing the cost of fabrication, paper and thin plastics becomes a viable alternative because it can obtain a variety of geometries and conductive features by using inkjet printing of conductive inks. These are important for fast prototyping, but they wear out faster than textiles or silicone [31, 51, 52]. The distribution of electronics around the body to reduce the volume of the design and avoid zones with complex shapes and movements were explored in SkinWire, which makes the connection lines handle deformations and movements of the body. Adding to this on-skin fabrication approaches, Electrodermis [43] presents fully integrated customizable bandages. Using a spandex base makes it reusable and feasible alternative to create body wearable electronics with a friendly interface that helps configure circuits, use a combination of electronics and modify fabrication parameters directly on scanned body parts. These stretchable skin simulating properties require multiple and complex fabrication methods to achieve the

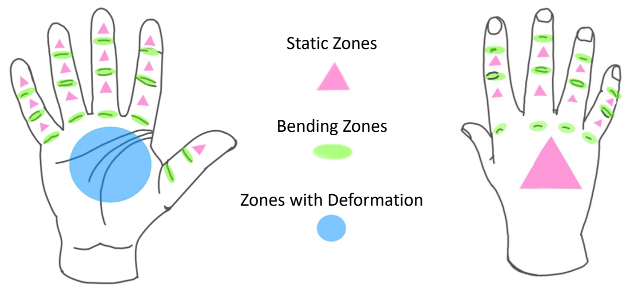

Fig. 3. Anthropometric and Empirical Analysis of Hand zones for Electronics Placement, Hand Parametrization Definition, and Hand Wearable template Design

required functionality, such as screen printing, sewing, and stitching, extrusion of conductive inks and pick and place processes [65, 70, 73]. To obtain these designs, users can directly design on skin printed features or use projections as if they were 3D printed on their own bodies [17, 18]. However, these methods do not involve electronics in the fabrication process. However, the above processes target multiple body zones, and it hinders to create a personalized hand wearable and does not always provide a robust product. SleekPatch proposes a combination between fashion and technology and merges conventional textiles with engineered conductive inks to provide a slim-fit wearable without any complex fabrication process that can be worn beneath other layers.

2.2 Hand Wearable Form Factors

Wearables for the hand have to adopt form factors which accommodate varying shapes, movements, and interactions of the users. Gloves represent the most popular alternative to create interactions [14], so they form a good benchmark to compare against even if they have a slightly varying design factor [6, 22, 38, 74]. However, they still house electronics on the wrists or on the back of the hand making them bulky and non-ergonomic. There are also wearable rings that have been widely explored, despite the limited space, [64, 72, 77, 83, 85, 86]. Different shapes and alternative locations other than full gloves and rings were explored such as NailO [27] that presents a wearable for fingernails enabling gesture and touch interaction. Also, Multi-shape adhesives that can adopt different geometries to adhere to the hand without a fully covered provide functionalities to generate interactions [25, 26, 43, 81] In this work, we propose a hybrid factor that uses an open form factor that can be easily attached.

2.3 Thumb-finger Interactions

The goal to achieve seamless and unobtrusive interactions has been explored using a variety of wearable devices. Thumb-finger interaction is one of the approaches that are well suited for the hand for interaction. They provide input modes for interacting with smart devices, head-mounted displays, and mobile computing in general. Users can input their commands by rotating a ring placed on the index finger [11] or use multiple types of touch inputs captured by different sensing techniques to enable such interactions [42, 50, 54, 74, 80]. Another important approach is the gesture-tracking using cameras or depth sensors, which are not too reliable as a tangible input device. Cameras and depth sensors are prone to visual occlusion and require expensive computation and configurations [38, 66]. Thumb-index interactions benefit eyes-free interactions, our approach intends to simplify the number of inputs and still provide a great variety of input modalities for mobile computing. As a general objective, the hand wearable should provide thumb-index input interactions, and remove the need for high precision, mid-air gestures, voice commands, or two hand interactions.

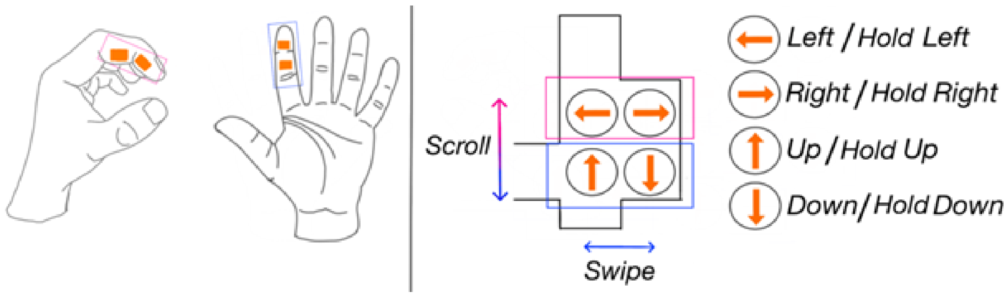

Fig. 4. Sensors location on the finger that enables the interactions and description of ten input modalities enabled by SleekPatch

2.4 Conductive Inks on Textiles

Creating functional circuits on wearable devices and garments have been approached in several works in engineering and fashion [61]. One approach in creating smart wearables is to screen print circuits directly on top of textiles to generate planar circuits [33, 35]. This exploration was based on understanding how inks and textiles get attach to each other [29, 30, 33, 56]. The use of Ultraviolet (UV) curing silver inks and carbon rubber over polyester/cotton (655) compounds has been studied in [79], and a review of textiles linked to applications and functionality and usage can be found in [75]

Our approach explores the compatibility of daily use textiles with commercially available inks to provide access to any user to create interactive hand wearables, expand the compatibility knowhow, understand the limitations of inks on textiles in current settings and when hand movements and manipulations are involved, and find an affordable way to fabricate e-wearables.

3 DESIGN CONSIDERATIONS AND FABRICATION OVERVIEW

Through the exploration of current fabrication methods, interactive hand wearables, and anatomical constraints, we defined the design requirements for our fabrication workflow as follows:

(1) Wearability – keeping comfort while performing activities and natural interactions with mobile technologies (R1).
(2) Slim design - to ensure a thin, lightweight, and interactive hand wearable that can fit beneath other gloves. (R2).
(3) Self-contained - to integrate all necessary components with no external attachments, while maintaining a slim design (R3)
(4) Durability - to enable multiple removal and application without disrupting regular functionality (R4)
(5) Mobility - facilitate interactions with mobile computing without being intrusive or obstructive (R5)
(6) Input modalities – enable various one-hand interactions as input modalities compatible with multiple mobile computing applications (R6).
(7) Social acceptability - should not make the user feel uncomfortable in a social environment, or people around when an unusual object is on the hands (R7).
(8) Simple fabrication – to afford a fabrication process without using complicated machinery or materials while maintaining a robust product (R8).

Table 1. Information about conductive inks. The dimension of the samples used were 0.65mmx42mm. The measurements collected from the 100% nylon samples

	Base material	Resistance (Ω) Measured (1 layer)	Curing Method	Substrates compatibility (Manufacturer)
Bare Conductive	Carbon	4.7	Room temperature - Fast curing	Paper. Plastic wood, wall, non-stretchable fabric
AP Wire Glue	Carbon	119K	Room temperature - Fast curing	Paper. Plastic wood, wall, non-stretchable fabric
Silver Ink Pen CSIP-998	Pure Silver	4.9	Room temperature - Fast curing	Paper. Plastic wood, wall.
CI-1036 Silver conductive Ink	Pure Silver	5.03	Room temperature - Fast curing, or 10 Minutes 120°C recommended	print treated polyester, Paper. Plastic wood, wall, Worthen NB-671W, transparent films, some stretchable films
841AR-P Nickel Plen	nickel flakes	24.23	Room temperature - Fast curing	smooth, flat, hard surface
841AR Nickel Coating	nickel flakes	24.2	Room temperature - Fast curing	smooth, flat, hard surface

4 MATERIAL SELECTION

In terms of creating on-body electronics being inspired by fashion trends, we combined materials from engineering and technology into textiles to achieve a simple and accessible fabrication approach. Our approach considers the combination of textiles with commercial conductive inks to simplify fabrication while retaining a slim form factor of the wearable. This methodology eliminates the need for soldering, stitching and sewing from the manufacturing process.

The process to integrate inks on substrates becomes complicated, costly, or even limited to some substrates suggested usually by manufacturers. Thus, this exploration represents an expansion of knowledge compatibility of current applications of conductive inks on some substrates. Ink properties such as stretchability, washability, or durability, change when the base substrate is changed [44], so it becomes relevant to identify the behaviour of ink and textiles in this fashion wearable integration.

- **Conductive Inks:** commercial conductive inks are highly conductive, and accessible. These inks allow the simple application of low profile circuits that can be easily adapted in shapes and sizes for aesthetic purposes. Our characterization considers carbon, silver, and nickel inks that are commercially available and are normally used over polymers, paper, glass, wall, and plastic [8, 48, 60]. These inks enable fast curing methods, and their easy application under home environments using DIY methods. We defined the number of layers to obtain a conductive trace to form circuits on textile, measured resistance of the formed traces, and also the compatibility with various textiles.
- **Substrates:** Selection of substrate is crucial in fabrication as it decides comfort, wearability, aesthetics, and can act as a bridge integrating technology with the body in a smooth transition [24]. Additionally, the substrate is responsible to hold the circuit elements, maintain functionality and reusability. The substrate needs to handle all degrees of freedom (DOF) of hand while maintaining a slim form factor, and enabling the possibility to work when covered by additional layers (i.e. gloves).
  The textiles were selected based on thickness, texture, rigidity, accessibility, comfort, softness, weight, unisex usage, and processing characteristics. Additionally, we considered combinations of these substrates that also satisfy these conditions. The substrates selected were 100% Polyester, 100% Nylon, 100% Cotton, 65% Polyester + 35% Cotton, 82% Nylon + 18% Spandex, and 90% Polyester + 10% Spandex.
- **Input requirement:** One-hand interactions were adopted as the input modalities for SleekPatch. Therefore, this input is achieved with thumb-index touch interactions and the interaction mode was implemented using touch sensors made with conductive materials. To this end, we used Velostat 1704 [67], and carbon filled elastomer [15]. The elastomer was added to the options because it can enable multiple thickness and shape configurations without any complex manufacturing processes. This thickness control will provide customization features for control and interactions while using the wearable.

Fig. 5. Samples of inks over 100% polyester

Other conductive materials such as carbon nanotubes, or PEDOT: PSS were not considered because they need additional complicated fabrication processes, and extra fabrication time [32].

4.1 Materials Evaluation

Materials were evaluated in two sections. First, we tested the compatibility between inks and textiles. This evaluation exposed the elements to physical tests that revealed the behaviour of various inks over textiles in all possible combinations. Second, we conducted a thickness and performance evaluation test to evaluate user's preferences with respect to touch sensitivities to different thicknesses using samples that passed the compatibility test.

4.1.1 Compatibility test.

This section of the evaluation consisted of exposing each combination of inks and textiles to physical tests, evaluating the bond between each textile and ink pair, and analyzing the amount of time under manipulation needed to stop the electrical conduction. The results were obtained visually and from the conductivity measurements on the samples

- **Samples preparation** We hand-painted three of interdigitated electrodes (Figure 10b) for each one of the six inks selected over each one of six textile samples cut in rectangles of 235 mm x 120 mm for a total of 108 electrode samples (Figure 5). The interdigitated shape was selected because of different line directions, and the fact that the template was used during the second part of the evaluation.
  The electrodes had a trace thickness of 0.65 mm and the sensing area had a radius of 0.4 mm. The thickness of the traces and the sensing area radius (Figure 5) were determined based on the hand painting process and the standard index finger width [10]. These parameters ensure that the sensor always fits on a finger and is easy to paint.

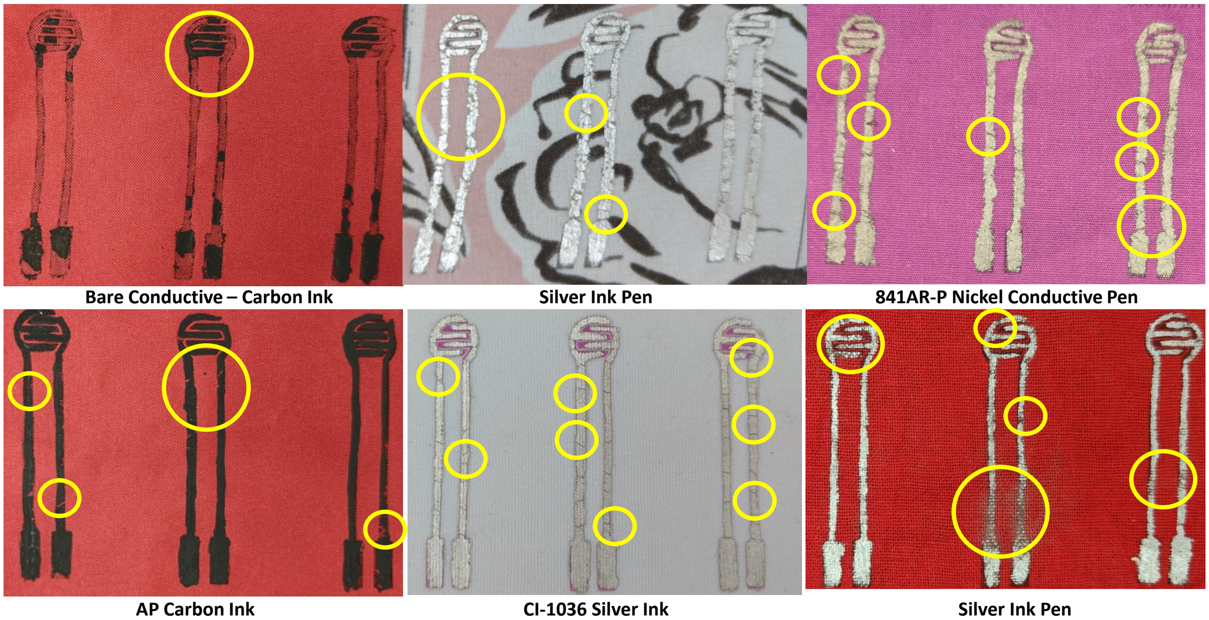

Fig. 6. Examples of the Results of the Compatibility Test. Circles indicate where the ink cracked or faded

The interdigitated pattern was selected because such pattern helps to reduce the volume of the sensor, improves control of the strength of sensor signal, reduces material and the number of layers, and generally simplifies the design, which allows the fabrication of most electrodes and conductors in a single layer [9, 41] (**Figure 10b**).

- **Test Description** The compatibility test between inks and textiles was performed exposing the samples to a slight bending, multi-directional movements, and storage in pockets. The textile samples were tested in five trials for 20 seconds. Then, we measured the conductivity of the traces after each trial.
- **Results** The compatibility test revealed that only CI-1036 silver ink passed the tests with 100% Nylon textile (100% of the trials), and with 100% polyester (40% of the trials). The rest of the inks cracked in the first trial of the tests. This limits the inks and textiles combinations to scenarios where there is no flexing, or bending, or stretching unless the textiles are specially treated. **Figure 6** shows the crackings and ink pads erased after the first event of manipulation (inside the circles).
  The stretchability of the textiles with a spandex component was an important limiting factor for this compatibility. The stretchability of fabrics was higher than the maximum stretchability of inks over these substrates.
  It is worth mentioning that the resistance of carbon traces was extremely high to be considered as an option to build the conductive circuits (Table 1) . In summary, the combination that continued to be tested in subsequent scenarios is CI-1036 silver ink and 100% Nylon. .

4.1.2 User Evaluation of Preference.

This evaluation explored users' preferences on thickness of the sensors and provided the optimal thickness from the users' perspective to achieve comfort while interacting with them using hands.

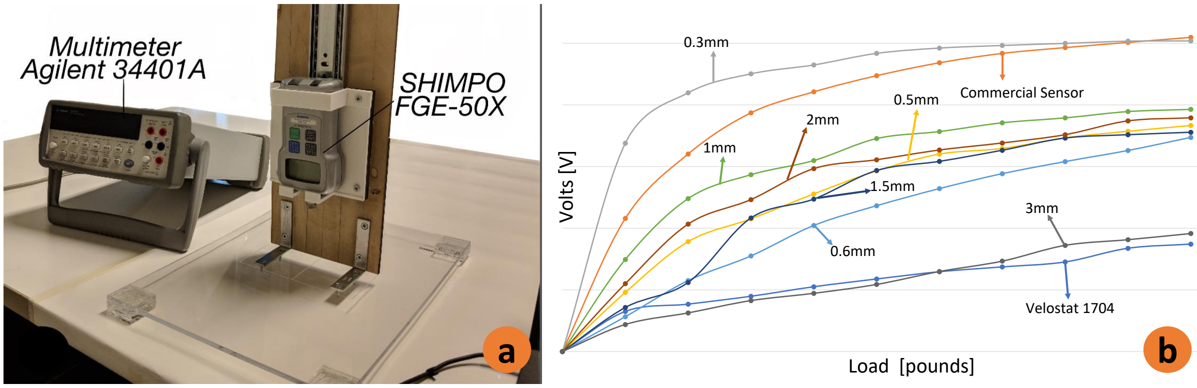

Fig. 7. a) Load test set up, b) Load results for each piezoresisitve sensor tested

- **Samples preparation** To prepare the samples, we fabricated an electrode and eight piezoresistive elements with different thicknesses (Velostat 1704 (0.1 mm), 0.3 mm, 0.4 mm, 0.6 mm, 1 mm, 1.5 mm, 2 mm, and 3 mm) and 0.8 mm diameter. The interdigitated electrode was painted using CI-1036 Silver ink over 100% Nylon textile which was the combination that successfully passed the compatibility test.
- **Participants** We recruited 12 participants with engineering background (6 Females) and ages between **22-35** (Mean = 24.17).
- **Test Description** The participants were asked to press the eight fabricated sensors one by one and to answer a Likert scale (1-10) questionnaire to evaluate the performance and touch sensitivity for each sensor. After the evaluation was performed, they were asked to interact with the sensors again in random order, select their top three preferences, and the worst sensor in their perspective. This process was repeated for all 12 participants.
- **Results** We collected results from the questionnaire given to the users and classified them using a 1-3-9 grading system [12] to detect the user touch experience. We observed that the sensors fabricated using carbon elastomer with a thickness of 0.3 mm and 0.4 mm were the favourite options among the users (8/12 users). These options satisfy users with regard to performance, touch sensation, response reaction, and control of pressure. It is also important to mention that the sensor fabricated using Velostat 1704 was considered as the least favourite. Users reported difficulties in knowing if they were pressing something and that the reaction time being too less to control the action exerted on it. From the users' perspective, we decided to use the 0.3 mm and 0.4 mm carbon elastomer-based sensors for fabrication and further evaluations.

4.1.3 Sensor Load test . The sensor response study was performed to compare the electric response between the sensors fabricated based on measurements of voltages generated from applying controlled loads. This will help in the selection of the optimal thickness of the sensor, and to understand the decision made by the users in the preference evaluation.

- **Samples preparation** This test used a single electrode with 0.8 mm diameter was fabricated using 100% Nylon using CI-1036 Silver ink. For the sensing piezoresistive layer, five samples for each thickness were fabricated. (Velostat 1704 (0.1 mm), 0.3 mm, 0.4 mm, 0.6 mm, 1 mm, 1.5 mm, 2 mm, and 3 mm).
- **Test Description** The test consisted of applying 10 different levels of controlled loads in a range from zero pounds to 3 pounds (incremental steps of 0.3 pounds) and measure the output voltage from the sensors caused by the load applied. We recorded 10 voltage measurements per load for each one of the five samples

of each thickness fabricated. Figure 7 display the average values for each one of the ten loads applied. This process was repeated for all the eight different values of thickness considered. The data was collected using a Digital Multimeter Agilent 34401A [13] and a SHIMPO Digital Force Gauge FGE-50X [59] to measure the output signals and the applied load respectively.

- **Results** From Figure 7 we can see that the curves that maintain a slow and uniform change are using the sensors with 1 mm, 2 mm, 0.4 mm, and 0.6 mm. Velostat and 3 mm maintain values that present variations of less than 0.7 V between the minimum and maximum values generated when is pressed. Finally, 0.3 mm sensor presents an abrupt change in voltage in the first two levels of load to generate and after that the variation is less of less than 0.5 V in the final measurements. This last sensor (0.3 mm) curve is the closest one to the commercial sensor curve.

We observe from all the three evaluations that the optimal combination for fabrication are CI-1036 silver ink for circuit traces and electrodes, 100% nylon textile for the substrate (compatibility test), and the 0.4 mm piezoelectric layer to complete the sensors (user preference and load test) for our interactive hand wearable.

5 FORM FACTOR DESIGN

To design and fabricate a wearable for a hand requires about twenty different measurements that vary between individuals [10], which makes it difficult a one-size-fits-all hand wearable. Moreover, when this wearable needs to include interaction points for the user, which adds more parameters and features to the wearable design. This variability in parameters leads us to define a form factor that considers material reduction, comfort, and manufacturing easiness as mentioned above in the design considerations.

The first consideration for the form factor is the one hand interactions, and inside this group, we selected thumb-index interactions because this provides enough space and options to generate interactions. Interactions with other fingers and the use of gestures were eliminated as an option because we want to limit the obstruction of the activities caused by the wearable. More options of interactions also add a considerable load to the memory of the users. Thumb-index interactions can be achieved independent of the user's skills and abilities because it uses natural movements. A good example of multiple inputs are popular consoles handheld controllers or TV remotes that have many buttons, joysticks, and touchpads to generate enough inputs to control applications. This number of inputs can be cumbersome, overwhelming, and not efficient for fast, everyday applications. Thumb-index interactions allow a wide variety of input modes such as touch, swipe, scroll, or bend that can be expanded depending on the applications. These inputs are also fast, common, simple, and natural [74].

Making the analysis of inputs, we define that for a click it is only needed one button, swipe two buttons, and scroll two buttons. A combination of three input buttons allows us to achieve all of them, which represents three-click options (using a simple input), two swipe options (left and right), and two scroll options (up and down) that combined represent 7 input modes. A four-button was added to add a feature for an easy navigation input implementation of up, down, left, and right as a navigation input modality.

To place these four inputs we start analyzing hand positions for these thumb-index interactions and selected the zones with most accuracy and comfort [5, 23, 36, 37, 68, 84]. Figure 3a, b presents the outcome of the anthropometric analysis made to find zones where the elements can be located. It shows critical zones that have a high level of movement or bending (blue circle, green ovals) and zones that present minimal changes when hands move (pink triangles). Thus, pink triangle zones become optimal zones for small electronic elements and sensors. Placing the sensors in the areas indicated in Figure 4a enables one hand interactions, reduce the number of physical parameters and materials for fabrication, and also contribute to the wearability of the garment [63, 64, 77]. In the case of the rest of the electronics that will process the information and communication with external devices, we are going to use the top of the hand (large pink triangle in Figure 3b) that provides enough space to distribute elements and does not present major movements when the hand is in use.

Using the locations defined for sensors and electronics, the shape of the template ensured to provide support to those elements, the interconnections among them, and to provide zones that help to fix the textile to the finger in a simple 2D template. This open design presents two important features. First, the textile goes with the ink traces along the palm side of the finger because in that way the substrate has to deal with bending conditions instead of stretching, which eliminates the tension feeling when the finger is bent. Second, it eases the wearable to be attache to the hand and also to wear it in as if it was not on the hand.

5.1 Sizing Application

The creation of a Personalized hand wearable becomes a major challenge due to the mentioned variety of hand sizes and shapes, and it is necessary for comfort purposes that will enhance wearability, one hand interactions, and fabrication. For example, ear-buds are sold with a combination of different sized of rubber earplugs to fit all users. However, hands are more complicated with more degrees of freedom, and because the addition of interaction zones, a general scaling of a design will not always work. Therefore, To achieve this adaptive form factor that can be easily fabricated, relocate input sensors, maintain a slim profile, while fully integrating all the elements needed, we proposed a sizing application.

The goal of the sizing application is to re-size the hand wearable to the user's hand measurements, relocate the input zones, consistency in the bending points among users, adapt compromised circuit zones, and generate a pattern for fabrication. This makes the fabrication of personalized hand wearables to become easier, and reliable. The graphical interface developed in Qt [55] shows the measurements the user needs to take to input in the system, and where those values need to be placed (Figure 8a). The user measures the length of the index finger phalanges individually, and insert those measurements where the application indicates.

After the phalanges measurements are inserted in the system and confirmed by the user, a rendering of the hand wearable template with the corresponding circuit implemented using OpenGL [53] is displayed on the screen interface as visual feedback of the new template created. Besides the circuit screen rendering, a DXF and PDF files are generated as an output. These files contain the base hand wearable substrate shape, the circuit template drawn, the voltage divider layer, and the input sensors layer shape. The application uses the inserted measurements to adapt the sensor location, bending points, and elements to every user's information.

The input sensors' relocation was achieved by referencing the position to the bending points of the finger because that is a decisive parameter that is not constant between users (green ovals depicted on Figure 3a). Hence, the zone where the sensor is placed on the finger will look and feel the same on any hand, which is going to benefit wearability, comfort, and interactions with the input sensors.

6 FABRICATION PROCESS DESCRIPTION

This section describes the fabrication workflow resulting from the integration of the material characterization, design template, and sizing application. The implemented hand wearable allows a robust fabrication, and reproducible process. This workflow simplifies the process in four main steps to fabricate a functional hand wearable (Figure 9).

6.1 Size Configuration

To define the personalized features of the hand wearable, the measurements of the three phalanges of the left index finger need to be entered in the sizing application. This software uses this information to determine the location of the input sensors and the bending zones of the finger. It also generates a printable pattern in DXF and PDF formats that contains the hand wearable template for the substrate with the fitted circuit on it. (Figure 9a).

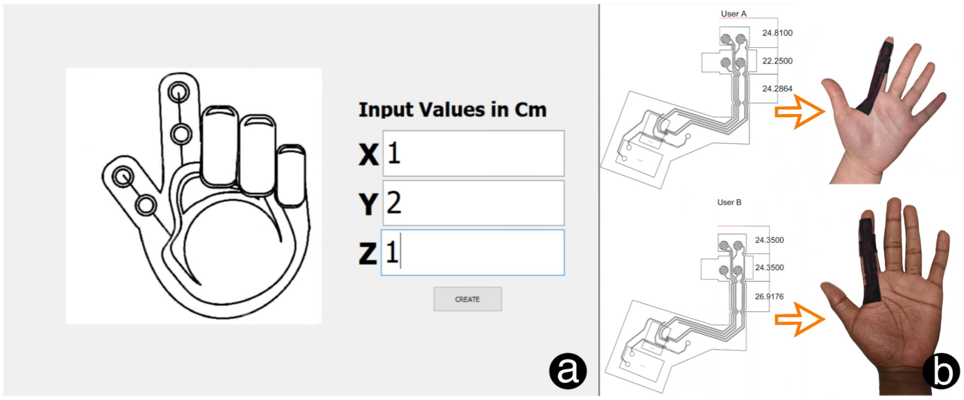

Fig. 8. a) SleekPatch User Interface. The user put the measurements of the phalanges in millimeters, b) Template Pattern Output and Users with two different hand sized wearing their designed SleekPatch

6.2 Transfer circuit to template

The template obtained using the sizing application is then printed over the textile (100% nylon) using a conventional color laser printer (HP LaserJet PRO 500 color). At this point, the ink can be applied to the template to trace the circuit. To do this, we decided to hand paint CI-1036 silver conductive ink [60] on the printed textile. The ink application can also be achieved by creating a screen, which later can be screen-printed on the textile. After the circuit transfer, the paint needs to be oven-cured for 5 minutes at 65°C to dry, make the paint conductive, and adhere to the substrate. After this step, the conductive lines are ready for the electronics and layer assembly.

6.3 Sensors Fabrication

The hand wearable developed can support both capacitive and piezoresistive sensing inputs. We directly use the interdigitated electrodes for the capacitive input, while we implemented sensors using Velostat 1704 and carbon filled elastomer for the piezoresistive one. Velostat 1704 needs to be cut in a circular form to work as a piezoresistive layer, while the carbon-filled elastomer version needs a more detailed process, which is described as follows:

- We based our carbon filled elastomer fabrication as previously described in iSoft [81]. First, the two components of ELASTOSIL LR 3162 are mixed in a 1:1 ratio [15]. Depending on the volume of the elastomer, it is recommended to mix for three to ten minutes to ensure a perfect blend. For the 4 electrodes, we used one gram of each component (2 g final weight) and mixed for 3 minutes. To obtain a cylindrical template with 0.4 mm thickness, we designed and 3D-printed a mold, using ABS-P430 material [4], in a MOJO 3D printer (3D printer configuration and resolution do not influence the result of the mold). Then, we placed the elastomer mix into the rounded molds using a palette knife and covered it with a layer of nylon textile, attaching the substrate to the elastomer. Then, a toaster oven was preheated (Mainstays 4-Slice Toaster Oven) to 65°C and the mold was placed in the oven for 12 minutes to cure the elastomer. After curing the elastomer, the mold was removed from the oven. In addition, once the material was cold, the cured elastomer was removed from the mold. (Note: if the elastomer is soft and cannot maintain its shape after the curing process, the mixing time was not sufficient. On the other hand, if the elastomer sticks to the mold, the curing time was excessive for its thickness.) Once the elastomer is removed from the mold, it is ready for the assembly of the sensor.

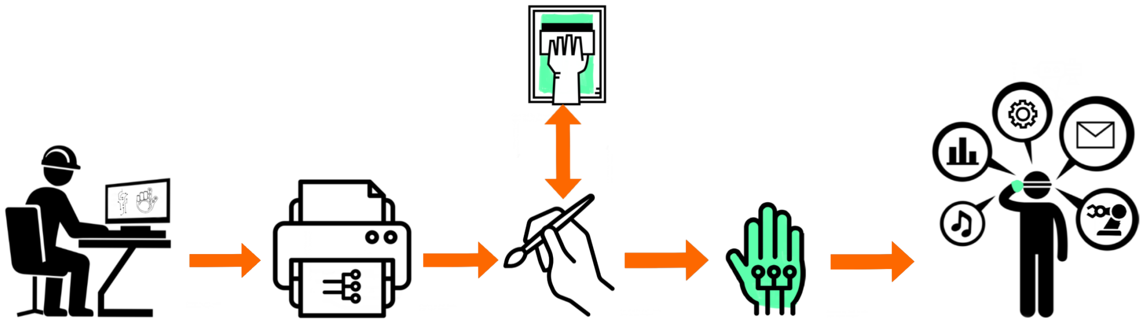

Fig. 9. Proposed Fabrication Workflow: Personalize Size - Print Template - Paint Circuit with conductive silver ink - Assemble Electronics - Wear (Screen Printing as an Alternative to Paint Circuit)

6.4 Layer assembly

The hand wearable is composed of four layers as shown in Figure 10a. These components are the base substrate containing the conductive ink traces, the processing/control/energy layer, the sensor layer, and the battery. To assemble these layers, we started by attaching the processing and voltage divider units to the base substrate. Using double-sided conductive Z-tape [2], we placed the elements on the assigned locations shown on the painted template. [2]. To ensure a solid connection and avoid additional layers, sewing or soldering, we then painted the terminals of the elements using the same silver paint used for the circuit traces. After this, we cured the recently added paint for 5mins at 65°C . Once cured, the sensors layer was placed on top of the electrodes painted on the base substrate. To fix the latest layer, the edges of the input layer were surrounded by textile double-sided tape [45]. Finally, the battery was attached using small square magnets, which ensures a good connection between the flexible circuit and the energy source. To attach SleekPatch to the hand, we used a layer of 3M 1509 double-sided tape [3]. This tape is a skin-friendly material designed for attaching devices to the body, and it is suggested to last for many days without losing its adhesion as other types of tapes. We tested such as the MIILYE Dress Body double-sided tape, and 3M 1522 clear tape [1, 45] which lose their adhesion in less than four hours.

After the entire fabrication process, SleekPatch weighs only 11 grams including the electronics and onboard battery. It is even lighter than the HoloLens™clicker that currently weighs 17 grams.

6.5 Data Processing

To read the changes from the sensor's signals, SleekPatchuses ESP32-WROOM-32 microcontroller from ESPRESSIF Systems. ESP32 includes analogue inputs, capacitive channels, and WI-FI capabilities, which are ideal for the application. The piezoresistive sensors were connected as voltage dividers to generate measurable voltage values. Using four 12 bit resolution analogue pins from the on-board microcontroller, we read the raw values from the sensors. The data obtained is then processed onboard and organized to recognize the user input interactions.

6.5.1 Input Modalities. Using the four sensor configuration we were able to achieve multiple types of one-handed input interactions. These input methods are used to access information and navigate on visual interfaces, scroll, swipe, and touch interactions that are common across devices.

As shown in Figure 4b we classify the possible inputs that can be generated and obtain around ten input commands based on clicks, scrolls, swipes and up to two levels of pressing.

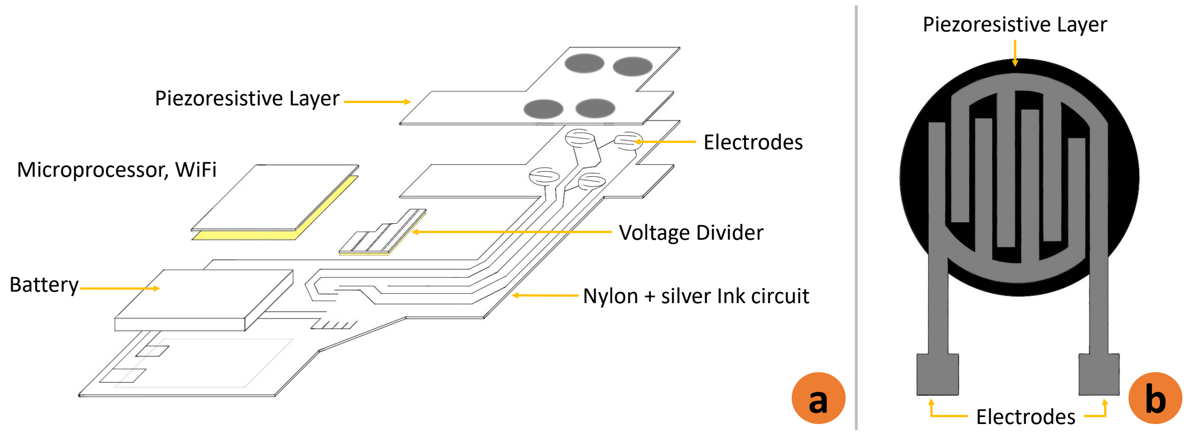

Fig. 10. a) SleekPatch Layers Assembly View. b) Interdigitated Sensor Structure Implemented in SleekPatch

7 EVALUATION

This evaluation exposed the hand wearable to two empirical evaluations that analyzed comfort and applicability of the wearable beneath other gloves. First, a group of users were asked to put on the wearable for eight hours continuously while performing usual activities. Second, we tested SleekPatch when worn under other types of gloves. We performed thumb-index interactions to analyze performance, and test if the form factor is thin enough to fit under the gloves.

7.1 Wearability and Social Acceptability Test

We implemented an evaluation suggested in SkinWire [26] as a very suitable alternative for testing prototypes. It incorporates details that do not need technical functionality of the devices but provide important insights about wearability and social acceptability of developing technologies. This test evaluated users in their own working environments while performing daily activities. The test was performed in natural settings for each participant. The purpose of the evaluation was to understand the behaviour of hand wearable in conventional not controlled settings and how the users feel about it while being in a social environment. Thus obtain insights on wearability, social acceptance, and durability.

- **Samples preparation** We fabricated samples of SleekPatch for each one of users with the Nylon textile, silver ink (CI-1036SP) [60], and 0.4 mm sensor that was found to be the best combination based on prior tests. Because of the test objective, the samples created were not functional but fully integrated because of the test goal.
- **Participants** We recruited seven participants (4M-3F) with an age group ranging between 21-30 years (mean = 24.85) for this test. They were selected based on their daily activities, so we recruited users with diversity in their activities such as fabrication, prototyping, office work, driving, programming, and designing.
- **Test Description** The participants were asked to wear the hand wearable to evaluate it during an eight hour period [26]. The main task was to wear it while performing routine activities. They were allowed to remove the glove whenever required and record the count. At the end of the test, we measured the conductivity of the samples to ensure that the traces were still functional. Additionally, we conducted a

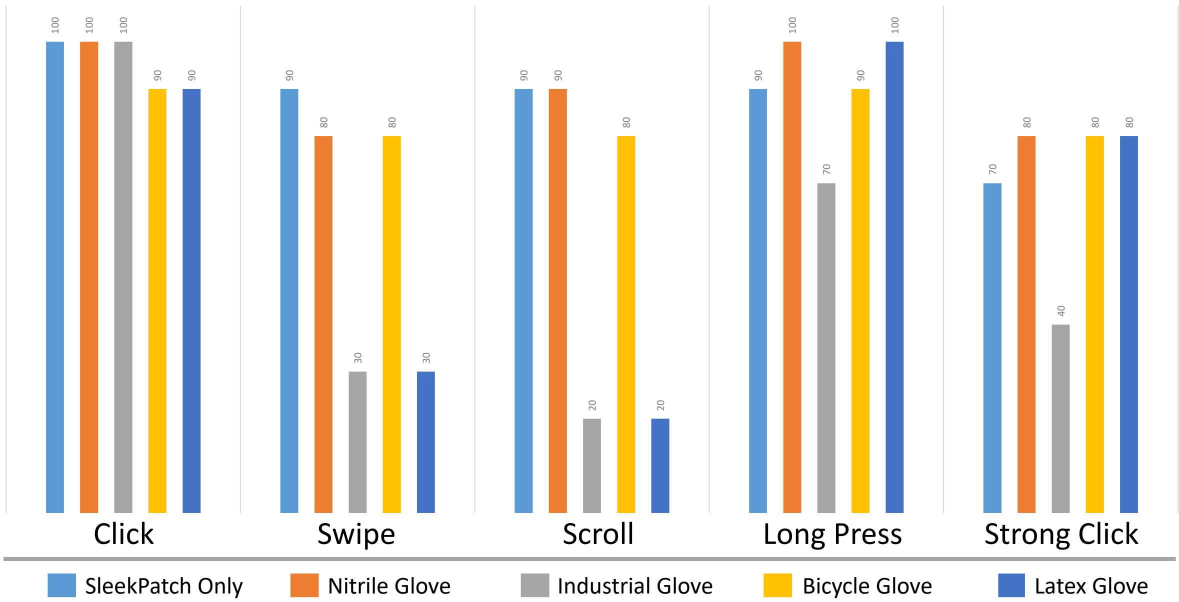

Fig. 11. Results of system under other gloves mentioning the interactions

questionnaire at the end of the test that comprises of both open questions and those based on a wearable scale [34].

- **Results** Three authors analyzed the data collected from the hybrid questionnaire, which comprised of questions based on Likert scale [34] and open questions using an inductive approach [62]. The objective was to gain obtain insight on how users perceive the hand wearable during a working day, in social environments and while performing normal activities. We discuss our findings in relationship to social acceptance, wearability, and comfort of SleekPatch.
  We report that all participants strongly agreed that the wearable is conveniently small, sleek, and not clunky. It was even considered as fashionable and voted positive about its appearance as an accessory. Six out of seven participants agreed that Sleekpatch design went well with their image and did not present a big contrast with their outfits. In terms of interactions, six out of seven were convinced that the hand wearable could provide multiple advantages in terms of applications. On the other hand, around half of the participants agreed that the wearable did not restrict their movements, while three of them mentioned that they felt some limitations. They reported that they had to remove the wearable several times (2 - 5 times) to perform activities like, washing hands, restroom visits, eating, and cooking. Finally, almost all participants, five out of seven, also reported that they just needed a few minutes to adapt to the wearable. Six participants reported that people around them found it acceptable to have the hand wearable, mentioning that the device was not creepy or that it would not make people uncomfortable. Five of them even commented that people might be interested in wearing it.
  Finally, participants reported activities such as using a computer, cutting using scissors, opening doors, eating, drawing, writing, soldering, typing, lifting boxes, driving and holding other objects while they were wearing SleekPatch.

Fig. 12. Figure of the 5 scenarios of the test - all the gloves we used

7.2 Functionality Under Layers

This evaluation explored the behaviour of SleekPatch under gloves. The goal was to evaluate the performance of the wearable when covered with gloves of different materials, textures, and sizes. The objective was to check if the wearable was thin enough to fit any scenario and to detect which interactions are limited by the layers.

- **Participants** This evaluation was performed by the researchers.
- **Test Description** We used SleekPatch to execute one of each basic input commands: click, swipe, scroll, long press, and strong click. Each action was executed ten times for each of the five different conditions: 1) SleekPatch only, 2) wearable under Nitrile glove, 3) wearable under the industrial glove, 4) wearable under bicycle glove, and 5) wearable under latex glove Figure 11.
  The test intends to evaluate the usability of commands in the current configuration, functionality under different layers.
- **Results**
  Figure 12 shows the results in each one of the five interactions and gloves tested. The best performance of SleekPatch is when the hands are not covered by gloves. The click interaction is consistent among the gloves and compared with the hand. We also observed that the industrial glove and the latex glove have difficulties at the moment of using the commands swipe and scroll. The industrial glove presents the lowest performance, and it only maintains the click and long press functional. In the case of the other gloves, they maintain the performance over 80% with the exceptions already entioned.

8 EXAMPLE APPLICATIONS

We developed four applications to demonstrate the applicability of SleekPatch. These applications show how SleekPatch can be merged into daily activities and how it provides superior functionality for interacting in public and mobile scenarios with no obstruction and subtle interactions.

8.1 Augmented Reality Interactions

8.1.1 Quadcopter assembly example. Inspired by assembly and instruction based toys, and AR instructional videos [39, 76, 78], SleekPatch was used to guide users in the assembly of a quadcopter using animated holograms displayed on a head-mounted device (HMD). The application describes a step by step sequence to assemble a quadcopter kit (Figure 13a). The user is able to control the sequence of steps by using left and right clicks to go back and forward in the steps when desired. Also, by holding one of the inputs, the user can play a small simulation on how to assemble the respective part. The left and right-clicking actions can be replaced by swiping

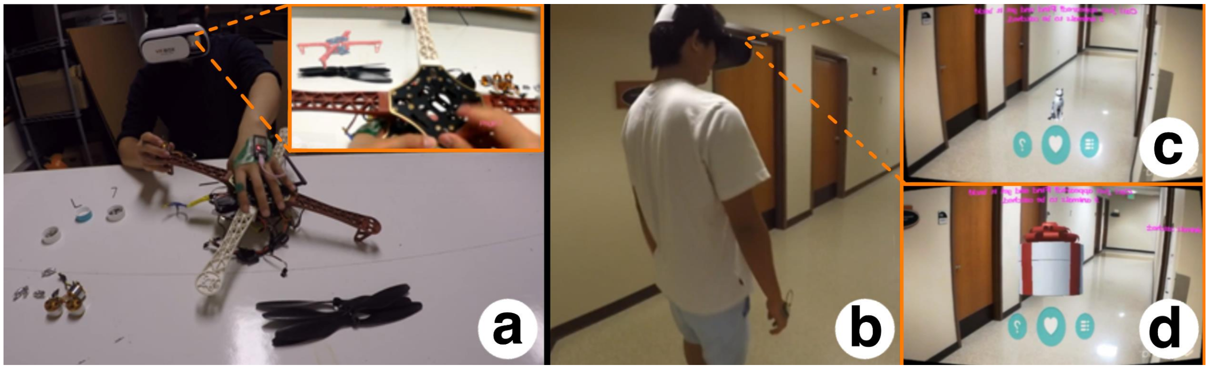

Fig. 13. SleekPatch Example Applications. a) Quadcopter Assembly, b) User walking on hallways to rescue animals, c) Animal found in a hallway, d) Animal cought in a box

actions to obtain the same functionality. SleekPatch enables the user to interact with holographic scenarios for assembly instructions without any obstruction in a simple way and without the need to gaze or point at the objects to interact, and interacting with tangible elements at the same time.

8.1.2 Dynamic scenarios and open environments. The immersion capabilities of mobile computing and wearable devices are well evident in activities such as AR games or fitness trackers that allow users to augment reality with recreational activities in open spaces and inspires this application. The animal catcher application allows users to play a game while moving. By swiping up or down using SleekPatch, the users can interact with holographic animals displayed on a HMD with an aim to catch and rescue the escaped animals. Additionally, the user can swipe left or right to access the menu or the questions section in the game too (Figure **??**). SleekPatch's non-obtrusive and natural interactions allow users to interact with devices while walking and avoid the need for hand-tracking to complete interactions.

8.2 Electronics Laboratory

An important feature of SleekPatch is the capability to work in any environment while covered by other layers. This feature facilitates the usage of SleekPatch while working in industrial settings, soldering, or manipulating biohazard materials. In this application, SleekPatch is assisting the user to control the phone while soldering electronic elements to his printed circuit board in a laboratory. (Figure 14a). This feature enables safe interaction under unconventional environments and work conditions, where SleekPatch can work beneath protective equipment such as gloves.

8.3 Smartwatch interaction

To demonstrate on the go, single hand, and fast interactions, Figure 14b shows a user interacting with his smartphone to answer an incoming call while walking on the street. Other applications with smartwatches can be typing, navigating between applications, or setting an alarm. This application demonstrates how users can interact with small screens without facing any obstructions caused by touch interactions while performing usual activities.

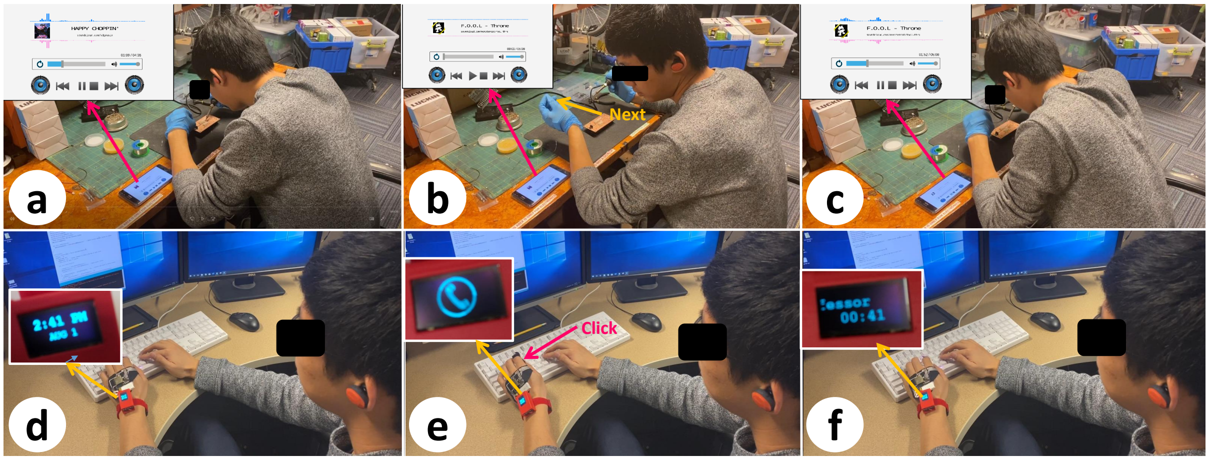

Fig. 14. Top: User working on soldering, wearing gloves, and using a music player, b) user changes the song using SleekPatch, c) user continues working normally. Bottom: d) user receives a call while programming, e) user answers the call with SleekPatch and continues normally his work

9 DISCUSSION

SleekPatch provides a fabrication workflow that contributes to the creation of self-contained hand wearables. In our studies, we demonstrated that our participants found SleekPatch comfortable and usable in a social environment.

The fabrication workflow proposed is a combination of a computer application and Do It Yourself (DIY) type technique. SleekPatch eliminates the load on the user, by providing a simple interface in which the user can input the measurements of the hand to design a usable form factor and obtain a template, after which the user can start the fabrication. Thus simplifying the decision-making of the user and provide a fabricable template with a suggested DIY fabrication process. We observed that a proficient painter–not necessarily an expert–could paint the circuit in approximately 10 minutes. The entire process which includes the three heat curing steps for the conductive ink and the elastomer and the installation of the components takes a total of approximately thirty-two minutes. We envision that this simplified method has the potential to popularize hand wearables and enable their integration into our everyday lives.

During the user studies, we observed that participants felt the design of SleekPatch to be conveniently small and easy to wear in a social context, suggesting it could be worn alongside different types of attires. The non-intervening nature of the wearable was shown in that half of the participants felt that the wearable did not hinder with their normal activities. In other cases where the hand wearable restricted some functionalities, participants mentioned that the limitation was not critical or uncomfortable. SleekPatch could be customized for each user, With an open form factor, SleekPatch enables easy removal and adaptability. Moreover, one of the users mentioned that it was somewhat difficult to get used to the wearable because the adhesive was not good enough, as it came out many times during the day. It is important to also mention that the hand of the participant had a certain amount of humidity caused by sweat and that this might have caused the adhesive not to adhere as expected.

Comfort plays a major role in a user's willingness to adopt a wearable. In the case of SleekPatch, the majority of the participants agreed that the wearable was comfortable and easy to adopt. Participants adapted to the wearable quickly and were able to perform their activities normally without getting distracted with the wearable.

One relevant aspect of the wearable was the adhesive interface between the material and the skin. This adhesive interface is a matter of concern not only forSleekPatch but for other works that suggest using off-the-shelf skin adhesives of some kind–typically used in medicine–as an attachment tool [26, 43]. While using skin adhesive was an efficient, reliable way to attach the wearable to the hand, some participants mentioned that the removal of the adhesive can be somewhat painful. However, as previously mentioned, these adhesives are commonly used within the medical community to treat patients. We tested different types of skin adhesives, but we did not consider the skin sensitivity of all the users when choosing an adhesive. This was mainly because skin sensitivity does not represent an issue of comfort and wearability, but only manifest itself when removing the wearable. Thus, since skin discomfort was not mentioned during the questionnaire, skin sensitivity was not considered.

Besides comfort, the small form factor and the nylon base substrate enable SleekPatch to merge with normal clothing and avoid drawing attention to the user's wearable, which was supported and appreciated by participants. Also, the input modalities benefit the interactions in public spaces because they can be performed inside pockets, under gloves, and without drawing attention to the user. This seamless integration will benefit interactions with emerging technologies such as augmented reality, which limit the users into midair interactions or button clickers and cumbersome controllers. Also, SleekPatch enables interactions with small screens and reduced spaces.

Finally, we propose our findings demonstrate how a simple fabrication workflow has the potential to create a slim and self-contained hand wearable. Also, this technology encourages the adoption of emerging mobile computing into a social context and our day to day activities.

10 LIMITATIONS AND FUTURE WORK

10.1 Scalability

During the evaluations and wearability tests, we observed that SleekPatchhad a limitation with respect to the minimum hand size. Hands with breadth smaller than 5 cm, do not provide enough area to place the electronics in current settings. This affects the use of children, especially for those under 6 years old [10]. We would like, in the future, to provide a version that can either move the electronics around or add a wristband version for smaller hands. This can be solved by creating more parameters on the wearable, and potentially more designs to fit very small hands. This small scale addition can promote the development of new applications for children.

10.2 Sizing

The current sizing application considers a limited number of parameters, based on the most used and accurate one-handed thumb-finger interactions. A future version will include more freedom to control over the parameters of the full hand measurements needed to design a hand wearable, and control over the size and number of electronic elements included. Another alternative expanding the control can be the addition of a full hand scan that allows users to manage the shape of the desired hand wearable without physically measuring. Additionally, we will explore the possibility of increasing the capabilities of the wearable to a full-body sizing configuration for interactions.

10.3 Fabrication

Our approach provides a fabrication pipeline that uses neither soldering nor sewing to create an electronic hand wearable, which benefits novice users. We focus on an affordable personalized fabrication, which can be improved in the future using laser cutters, 3D printing techniques, and other paint transfer techniques such as inkjet printing. This makes the fabrication process faster, easier and can allow improvements in wearable geometry. In the future, It is intended to explore the combination of polymers with textiles and other fashion elements that can enhance the functionality and wearability.

11 CONCLUSION

We introduced SleekPatch, a fabrication workflow that generates a fully-integrated, light-weight, and slim, interactive hand wearable that is socially acceptable and enables interaction with mobile computing. SleekPatch uses a wearable 2D template generated by a sizing application that uses the phalange measurements of the index finger to reposition the input sensors according to each user finger measurements. Enabling users to position the sensors in the same finger locations while accounting for different users independent hand sizes and shapes. This process along with the combination of the results in the materials characterization eliminates the need for conventional fabrication techniques that involve soldering and stitching.SleekPatch intends to keep fashionable wearables while integrating technology to create personalized interactive wearable devices. We also observed the behaviour of conductive inks painted over textiles and their performance under conventional wear and normal everyday activities. These observations show that silver ink with heat curing [60] on a 100% nylon substrate present a solid and durable bonding for a hand wearable. This fashion and technology approach implemented in SleekPatch enables the possibility to fabricate socially acceptable robust interactive garments. We hope technology such as SleekPatch encourages more users to utilize DIY fabrication techniques to integrate technology and mobile computing into everyday lives The purpose of SleekPatch is to encourage and promote the future development of applications using our fabrication approach, encourage more research into hands-free input modalities and the design of low cost, low profile fully integrated wearables.

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To Robert, for the bagels and explaining CMYK and color spaces.

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