FabHandWear : An End-to-End Pipeline from Design to Fabrication of Customized Functional Hand Wearables

LUIS PAREDES, Purdue University, USA
SAI SWARUP REDDY, Purdue University, USA
SUBRAMANIAN CHIDAMBARAM, Purdue University, USA
DEVASHRI VAGHOLKAR, Purdue University, USA
YUNBO ZHANG, Rochester Institute of Technology, USA
BEDRICH BENES, Purdue University, USA
KARTHIK RAMANI, Purdue University, USA

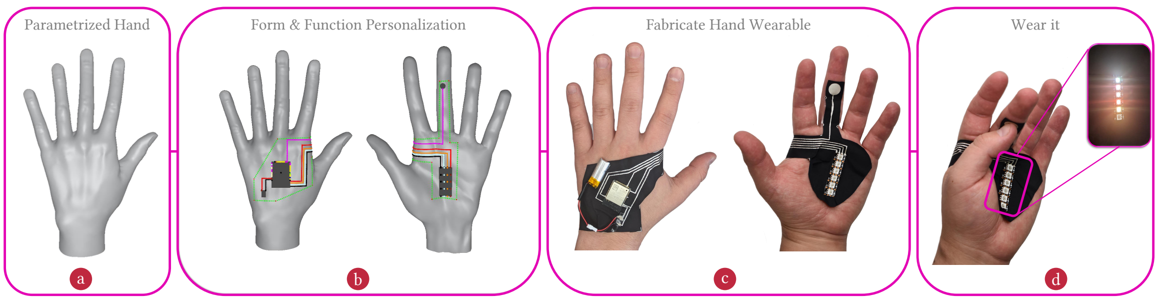

Fig. 1. A 3D parametric hand model (a) is interactively customized by adding electronic components (b) by using FabHandWear and then fabricated (c). The printed wearable device has the desired shape and function (d) .

Current hand wearables have limited customizability, they are loose-fit to an individual's hand and lack comfort. The main barrier in customizing hand wearables is the geometric complexity and size variation in hands. Moreover, there are different functions that the users can be looking for; some may only want to detect hand's motion or orientation; others may be interested in tracking their vital signs. Current wearables usually fit multiple functions and are designed for a universal user with none or limited customization. There are no specialized tools that facilitate the creation of customized hand wearables for varying hand sizes and provide different functionalities. We envision an emerging generation of customizable hand wearables that supports hand differences and promotes hand exploration with additional functionality. We introduce

Authors' addresses: Luis Paredes, lparede@purdue.edu, Purdue University, 610 Purdue Mall, West Lafayette, Indiana, USA, 47907; Sai Swarup Reddy, Purdue University, 610 Purdue Mall, West Lafayette, Indiana, USA, 47907, reddy37@purdue.edu; Subramanian Chidambaram, Purdue University, 610 Purdue Mall, West Lafayette, Indiana, USA, 47907, schidamb@purdue.edu; Devashri Vagholkar, Purdue University, 610 Purdue Mall, West Lafayette, Indiana, USA, 47907, dvagholk@purdue.edu; Yunbo Zhang, Rochester Institute of Technology, Rochester, New York, USA, 14623, ywzeie@rit.edu; Bedrich Benes, Purdue University, 610 Purdue Mall, West Lafayette, Indiana, USA, 47907, bbenes@purdue.edu; Karthik Ramani, Purdue University, 610 Purdue Mall, West Lafayette, Indiana, USA, 47907, ramani@purdue.edu.

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FabHandWear, a novel system that allows end-to-end design and fabrication of customized functional self-contained hand wearables. FabHandWear is designed to work with off-the-shelf electronics, with the ability to connect them automatically and generate a printable pattern for fabrication. We validate our system by using illustrative applications, a durability test, and an empirical user evaluation. Overall, FabHandWear offers the freedom to create customized, functional, and manufacturable hand wearables.

CCS Concepts: • **Human-centered computing** → **Interactive systems and tools**; *Systems and tools for interaction design*; • **Hardware** → Emerging interfaces.

Additional Key Words and Phrases: Wearables; hand; 3D design; fabrication; customization, electronics, interface, inks, textiles, screen print

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1 INTRODUCTION

Hands have evolved into a universal and versatile tool to manipulate and sense objects. For a long time, dexterity of hands has been leveraged in creating art, playing musical instruments, or even in culinary skills. Within the HCI community, hands have been extensively used as a means of user interaction. We use hands to input information using a keyboard, navigate the screen using a mouse, VR interaction via controllers, or direct hand gestures such as in the recent Quest 2 [63], or Hololens 2 [55]. Mobile computing devices based on touch input from fingers have exploited different gestures such as pinch, swipe, double-tap to accomplish different functionalities. Hands are always available and allow users to text, grasp, touch, sense, or move content using mid-air gestures, phones, or handheld controllers. To augment our hand's existing potential developing wearables around them can open doors to many new applications. For each wearable, the design and form factor depends on the application, the user, and the components in use. Wearable technology enables the possibility of adding instrumentation and merging computing intelligence into our hands [32, 76, 100].

However, hand wearables are challenging to design and fabricate because of the anatomical variability in hand forms, multiple degrees of freedom, and absence of standard manufacturing techniques. These challenges influence the accuracy and comfort of hand wearables [31, 39, 98, 99, 103, 104] Additionally, the hand wearables' form factors are bulky, protrusive, and are not customizable, which represent additional barriers [31, 95, 98]. Interaction designers create large prototypes with obtrusive wires to accommodate different hand shapes and component locations during evaluations. Perret and Vander Poorten [69] review of haptic gloves for Virtual reality comment that an effective hand wearable must be adaptable to the user, fit arbitrary size and form of the hands, and the components need to be relative to the anatomy of the user.We envision that designing hand wearables should be simpler and faster to enable the testing of new sensing technologies, interactions, or haptics. Easing the hand wearable creation will provide access to prototype technology quickly and accurately to multidisciplinary groups of designers with different expertise levels.

Wearables usually integrate multiple functions, and they are designed for a universal user with either no or minimal customization. There are several CAD tools with lower entry barriers catering towards creating customizable Do It Yourself (DIY) products such as TinkerCAD[11, 58, 82], but there are no accessible tools that facilitate customized wearables design. Creating hand wearables with multiple electronic components is not an easy task, as the design and fabrication methods available are too general for specific parts of the body. Hands highlight those limitations and require extra effort from designers to combine those practices to create hand wearables [4, 16, 76, 100]. Using magnetic, infrared, capacitive, or other large sensors and hand tracking systems is hard to accommodate in conventional manufacturing techniques. Supporting multiple interconnected islands of standardized modular electronics around the body is one way to reduce the bulkiness of wearables [36, 54, 89], which again limits the electronic components to a predefined set of standard modules and thus prevents the user from exploring additional functionalities.

These limitations are exacerbated when the design process combines those components because the issues encountered are usually carried into the fabrication and later into the wearability, performance, and aesthetics of the wearables [12, 16, 39, 91]. Hand wearables should provide small form factors, seamless interactions, unobtrusive designs and must adapt to the user shape and needs [17, 24, 36, 39, 54].

We introduce FabHandWear, a framework with an integrated fabrication approach for creating self-contained functional hand wearables. FabHandWear brings customization of form and functionality in a series of simple and guided steps. It allows users from many knowledge levels and backgrounds to explore and prototype new hand interaction, sensing, and input modalities. The difference with other approaches is that FabHandWear integrates fabrication and hand anatomical constraints into the design tool to provide an assisted, simplified, and efficient creative process.

We realize that designing on hands requires determining the size and available working area, functionality, list of components, distribution, and the interconnection of components. The design process with FabHandWear provides the user with a parametric 3D hand that users can transform to represent their hand closely. Onto this 3D shape, designers can place the electronic components that define the desired functionalities of the wearable. Designing on a 3D hand allows better visualization and perspective on the location of the components and a more natural experience [21, 22]. As shown in Figure 2, the designer uses the side menu to personalize the hand size measurements, select the electronic components, and generate the printable pattern. After personalizing the hand measurements, the designer selects components from the list and places them on the 3D hand. The user can translate or rotate these components on the 3D hand until he is satisfied with the design. After finishing the design, the user enables the circuit creation, which creates a viable set of circuit traces. Finally, FabHandWear generates the substrate shape based on the user's input and desired fabrication shape. In case the design requires a component not included in the library, we allow the user to add new components, which will enable our application to stay up-to-date with new developments of wearable technology components.

Creating the substrate is the end of the design phase. Next, the tool translates the design from the 3D hand to a 2D printable pattern comprising an open design structure of the hand wearable. The open structure of the wearable enables customized fitting and ease the fabrication process. The printed pattern is the template for creating the screen used to screen-print the circuit traces over a substrate. FabHandWear uses conductive silver ink to create the circuit traces over a waterproof nylon substrate. The nylon substrate serves as structural support for the electronic components and makes the wearable reusable. Once the circuit traces are screen printed over the nylon, the user places the components on the textile and uses heat to cure the conductive traces and fix the components. Finally, FabHandWear can be worn as a patch using a skin-compatible double-sided adhesive, and the fabrication is less than an hour.

To evaluate our system, we first conducted a technical evaluation that defines material compatibility when exposed to stress produces by continuous bending. Second, we developed five different applications that demonstrate applicability, functionality, and different levels of complexity that FabHandWear can support. Lastly, we conduct an empirical user evaluation of the tool to illustrate the usability and fitting for users with diverse backgrounds. In summary, our contributions are:

- The integration of hand anatomical constraints and fabrication limitations to design manufacturable hand wearables.
- A design tool that allows personalization of form and function of hand wearables. By enabling the users to design the wearable over a 3D model of a which is later transposed to a 2D surface for enabling fabrication.
- A simplified fabrication workflow that does not require complicated equipment or advanced skills to achieve a functional device.

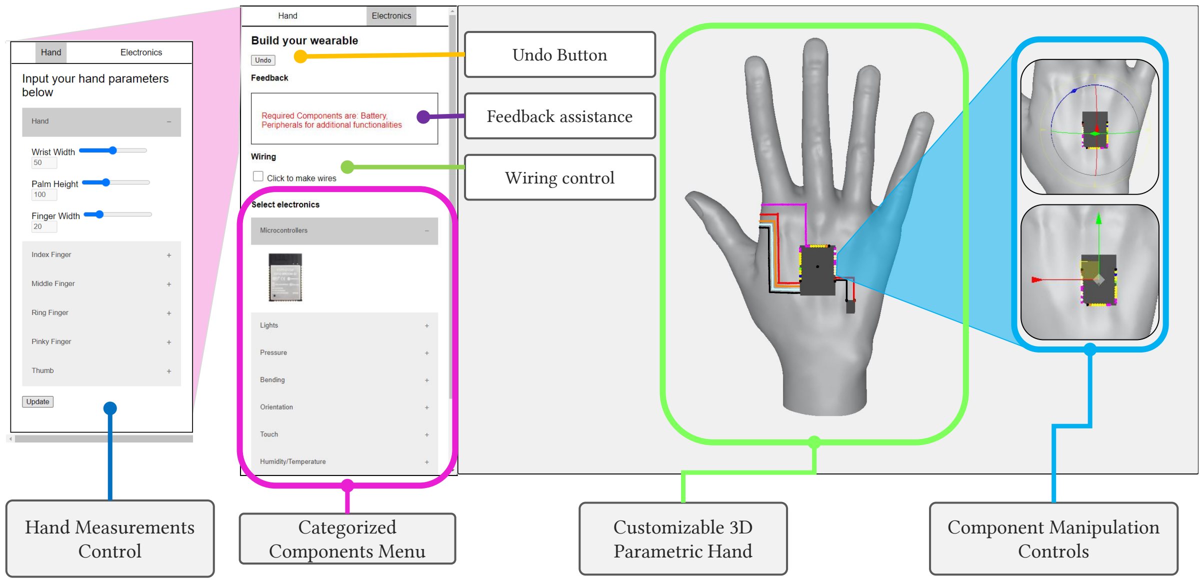

Fig. 2. FabHandWear Design Interface - Sections Description

2 RELATED WORK

2.1 Wearable Fabrication Techniques

The extensive exploration of wearable fabrication techniques demonstrates the need and potential to create interactive interfaces. However, these techniques are developed for a wide spectrum of applications, leading to large and bulky wearables that lack specific anatomical considerations. A standard but effective methodology is the integration of rigid electronics through sewing and stitching components onto garments [6, 24, 39, 75]. Designers use conventional circuit methodologies to attach functionalities to the garments. The technique is improved by adding conductive threads [35, 57, 68, 70, 79], tapes [54], or textiles [29, 43, 78] used as conductive traces to form the circuits to ensure reliable and robust integration of electronics on textiles. The limitations of this methodology are the large-bulky electronics and the complexity of implementation, which reduces the number of designers that will access it.

The need to reduce the size, bulkiness, and complexity of manufacturing led to experimenting with the integration of new materials such as conductive inks and tapes [81]. These new conductors create an opportunity to use other substrates and manufacturing techniques. Inks, in particular, could be applied using screen printing [62, 66, 72], inkjet printing [10, 40, 42, 64–66, 73], which enables a fast and precise methodology to create thin conductive traces and prototype wearable devices.

Previous techniques add conductive materials and electronics to modify commercial modify textiles or garments. Moreover, they could only be available when the garment is worn. Taking the device wearability to a new level, the exploration of skin electronics opens the possibility of carrying these interactive devices by attaching them directly to the skin. Water transfer tattoos are the more convenient and cost-effective of these techniques. The circuits are created by printing conductive materials over the tattoo paper and then transferred to the body surface desired [36, 38, 49, 60, 62, 90, 92, 97]. The fragility of these wearables makes them not reusable nor reliable. The idea to develop skin electronics expanded to develop skin-like devices. Wearables that can stretch as much as the human skin and can be as seamless as possible. The use of various polymers such asPDMS [59, 91, 94], PEDOT:PSS [25], Ecoflex [75], PET [41, 62, 99] help emulate the skin like objective for wearables. However, their durability is still limited, and the fabrication presents a high level of complexity.

FabHandWear builds on this body of work. We prioritize screen printing as it is easy to learn. It enables the fabrication of thin circuits and can be implemented in DIY settings while maintaining a robust, reusable, and reliable hand wearable device.

2.2 On Body Fabrication Tools

A wearables design tool should allow designers to control body location, features, and dimensions of the desired wearables [61, 85]. The diversity of styles, manufacturing techniques, and size of components have limited the development of wearables with these characteristics integrated into a single device. To simulate the conventional design process, DressUp uses a physical mannequin as a prop to capture the designers' drawings and then transfer them into a screen for visualization. Allowing designers to have full control of what they design and with no many new procedures to learn [96]. Similarly, systems that track body parts using external camera tracking systems allow designers to create their designs directly on the body. While exciting and very accurate for sizing, this process requires continuous tracking, and depending on the body part selected, it can be uncomfortable and limiting [21, 22]. These limitations expose the need for digital body representations to design on body parts and with all the freedom of the body. These tools allow users to visualize, simulate, and create fabricable patterns of those wearables. Using the body as a base model, designers can use CAD and surface modeling techniques to manipulate their wearables digitally [87, 88, 105]. Unfortunately, these tools do not integrate electronics into the wearables designed. Integrating these limitations and adding functionality into the wearables, Electrodermis enables functional adhesive patches o create flat patterns based on the user's 3D scanned body part. The designers scan the body zone for the wearable and then draw a contour to define a 2D surface. This surface is the working area to add the desired functionality to the wearable patch [54]. A recent work [81] assists designers to check the trace conductivity of wearables fabricated using thermal in-mold process. Their work focuses on detecting conductivity changes of the traces before and after forming. The Polyethylene terephthalate (PETG) material used in the in-mold process is very limited in making wearables, especially for hands.

FabHandWear enables users to design directly over a 3D hand geometry simulating the on body design principle. This method improves visualization, dimensions control, and precise elements location over the complex geometry of a parametric hand.

2.3 On-Hand Wearables

Hand anatomy and the number of degrees of freedom have pushed the exploration of hand wearables to present different shapes and structures to achieve specific functionality. This wearables structure depends on the kind of information required and the location of the sensing components. The use of full covering gloves used as a base substrate to attach sensors and actuators presents the most benefits in terms of space [8, 15, 16, 30, 47, 95]. However, for some applications, gloves are bulky, unnecessary, or invasive. For those applications, the use of rings [67, 102], patches or tattoos [38, 60, 91, 92], or only strapping or sticking electronics on the finger does not need to cover all the hands to perform as expected [37, 93, 103].

All these form factors open a variety of possibilities for applications. Hand wearables enable different methods of hand tracking and gesture recognition systems [8, 47]. It allows users to interact with multiple systems by using thumbs-finger or thumb-index gestures [83, 98, 103, 104], haptic feedback [97], or other types of touch and tap inputs [32, 62, 101]. FabHandWear creates this physical structure based on the functionality requirements personalized by the users. It uses an open form factor that facilitates the wearing and sizing.

2.4 Circuit Routing

Despite the availability of software for PCB design creation [18, 19], barriers exist for customizing wearables, because of their bulkiness and complexity, especially for users that are unfamiliar with electronics and circuit design. The process is time-consuming, prone to errors, and requires electronics knowledge to achieve successful results. A common method to create circuit traces is by manually drawing [13, 50, 84], sewing conductive materials [26], transferring with heat [43], or drawing by using tablets [51], which requires skills and dexterities to achieve small and simple circuits. Illustration software can overcome the size and accuracy limitation of the circuits. The designers can create templates of the circuits that later can be inkjet printed or screen printed. This process facilitates the fabrication, but the user is still required to have electronics and circuits knowledge to create the interconnections [92] To alleviate the load or circuit and electronic knowledge, designers have approached the circuit design by limiting the number of components by using libraries with predefined interconnections. The user selects the components and places them where desired. The system then handles all the interconnection of pins, which is an excellent solution for predefined components [54, 89]. However, the ever-expanding library of components and electronics increases the number of applications and makes predefined connections an unsustainable long term solution. Various approaches, such as LASEC [25, 74], enable circuits over a flexible cut substrate with conventional SMD electronics. By using three rules for the circuit: search for less stretchable areas, generate parallel circuit lines, and allow the modification of the cut patterns.

FabHandWear enables circuits over the 3D surface and the complicated geometry of the hand with quick and straightforward steps for users with limited knowledge of electronics.

3 PRELIMINARY PILOT STUDY:

Fig. 3. A participant typing on a head mounted display using a hand wearable

We wanted to analyze and understand users interacting with a wearable that is not entirely fitting on their hands. Conventionally, developers first define the best locations to place sensing elements on the hands before designing the wearable [34, 39, 98, 99]. This critical step can determine the success of the interactions according to those studies.

To verify this assumption, we recruited 10 participants with multidisciplinary backgrounds using university email distribution (five self-identified as female and five as male) with ages between 22-36 years old (age mean = 27.3 years, std = 4.57). The participants did not require any specific previous experience to conduct the study.

Participants had to navigate on a "qwerty" keyboard implemented by using a head-mounted device. The user controlled the keyboard navigation with a textile-based hand wearable with four touch sensors placed on the index finger. The hand wearable was sized using one of the author's hand measurements selected randomly (Figure 3). The study intended to obtain insights into how the participants react to an inadequate wearable size and their impact on their experience. We record and observed their interactions with the wearable and collect comments about their experience survey. Using a deductive approach, the data collected reveal important features about configurations and material requirements to develop a hand wearable [14].

Observations revealed how the size of the wearable changes the location of the sensors, which is reflected in the users' experience and comfort while interacting with the wearable. Participants need to see their hands to perform the interactions several times and to reach uncomfortable zones [98]. Independent of the hand and the wearable ratio, the adhesive peeled from the joints sections after some hand movements.

Keeping the wearable attached to the hand is a wearability feature that must be satisfied. The users whose hand size was close to the size of the wearable maintain the wearable for the period of the test. the size, the attachment mode, and the continuous wearability are the features considered as requirements for the fabrication process of the wearable and further translated as part of FabHandWear [27, 44, 45, 48, 71]. Finally, participants reported to be indifferent to the preferred hand to wear a wearable and that it will be interesting to adapt the buttons' location. To implement a methodology or a system that allows people to fit their wearables to their anatomical and application needs, we identify a set of requirements that assist in designing and fabricating hand wearables.

3.1 Design Objectives

To enable the design with our system, we considered the multidisciplinary nature of wearables and the knowledge levels of the users. The design will comprise the functionality, size, and shape customization, while the fabrication will have to adapt to allow fast and straightforward procedures. We grouped the requirements into the following five main objectives:

- **O1. Functionality:** users should be able to select, add and modify electronic components to create functional circuits.
- **O2. Customization:** users should be able to modify the size, shape, and functionality of their wearables at any time. These modifications will allow the design to fit the wearable as desired and to place components where needed.
- **O3. Fabricability:** users should be able to implement the created designs with no need for complex equipment and special skills to create functional wearables. These will reduce the skills and knowledge barrier requirements to prototype the designed wearables.
- **O4. Visualization:** users should be able to visualize the customization during the design process. The system should provide a 3D hand model visualization to improve perception during design.
- **O5. Open Ended:** Users should be free to design their applications and create new shapes, applications, and components.

The objectives are part of the system as part of the Interface interaction (O4), design workflow (O1, O2, O5), and fabrication process (O3).

4 DESIGN TOOL - FABHANDWEAR

The design tool's objective is to facilitate and assist in creating customized and functional hand wearable templates that can be used during the manufacturing process. The main features of the tool are geometric and functional control, ease in circuit connections, auto-circuit generation, substrate creation, and printable pattern generation. All the functions were implemented in JavaScript using three.js library [80] to support a web-based application.

Our design process starts with a parameterized 3D hand model as a base for users to begin designing the wearable. The user then adjusts their virtual hand model parameters with the desired finger, palm, and wrist measurements. After which, all required electronic components are placed over the 3D hand mesh model. FabHandWear is capable of auto-generating the circuit traces based on the information regarding the electronic components and corresponding pins (obtained from XML, refer to section 5.3). The tool also allows the user to manually connect the placed electronic components using the color-coded system, denoting the functions and compatibility of the pins. Depending on the level of expertise of the user, the circuit can be auto or manually generated. Finally, the user can design the substrate, after which FabHandWear will generate a 2D template to start the fabrication.

4.1 Adapting 3D Hand Model

This process allows the users to adapt the base 3D hand model to the desired hand size. The user measures hand dimensions using a ruler or a caliper and enters them into the interface. Those measurements adapt the 3D parametric hand model to the input values of the user. The model has control over phalange lengths, finger spacing, palm measurements, and hand thickness, representing access to a total of twenty-one configurable measurements.

4.1.1 Reasons for Hand Parametrization. Designing and visualizing in 3D enhances the perception of the components' size and position over the hand [21, 86].

The parametrization was selected to satisfy five main conditions:

- Simplify user intervention: No 3D scanning or geometry segmentation.
- Ensure template precision: Reduce the uncertainty in the fitting of the fabricated wearable.
- Accessibility: Remove the technology dependency barrier from the design process.
- Easy design migration: A single design can be adapted easily to multiple users by only changing the measurement values.
- Standard base template: To reduce errors with 3D scanning features and hand poses.
- No template flattening: Removes the need to flatten 3D geometries.

4.2 Electronic Components Placement

FabHandWear uses off the shelf electronic components without modifications and created parametric components(electrodes for touch sensors and bending sensors). We use ten different menus to classify and store the electrical components, based on the functionality (micro-controllers, LEDs, pressure, bending, touch\capacitive, orientation\acceleration, humidity, power, vibration, switch, headers). The user selects a component from these menus and places them in the desired location over the 3D hand model. The functionality menus assist users with a basic level of electronic knowledge to find the desired component faster.

During the components selection, the tool displays a list of electronic components needed to complete a functional circuit. The list uses the elements placed over the hand model and updates after adding a component. For example, when a user places a bend sensor over the index finger, the tool will display a list using the functional groups. For this example, *"microcontroller, voltage divider, switch, and power"* is displayed, which is an assistive feature that ensures the user places all the components required for a functional circuit.

4.3 XML Protocol

To let FabHandWear know which pins of what component has to be connected and determine the compatibility among different electronics,

we used the XML file format to create a generic template for each electronic component. We build on previous work and XML files on transferring information across platforms to implement a fast and space-efficient protocol

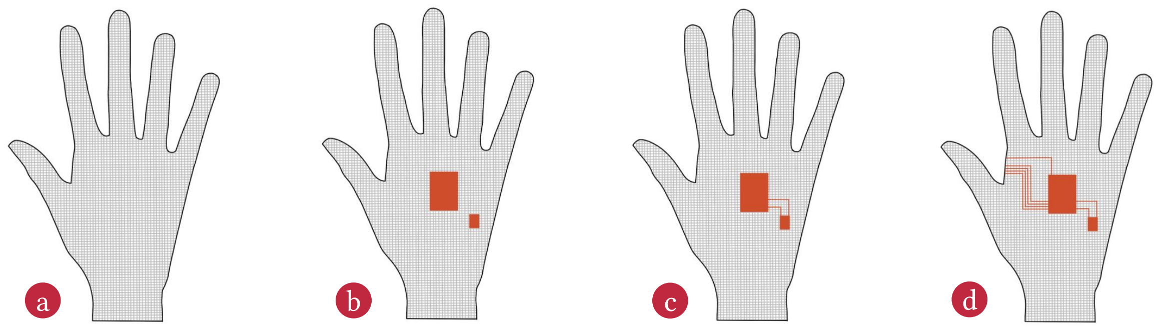

Fig. 4. The hand model is discretized with a 2D grid (a). After the circuits are positioned (b) the tool automatically finds routing connection of the components (c) and sensors (d).

for adding new components to a library [53]. We created a generic template for electronic components to ensure the users add all the necessary information to the new component in the database [46]. The template contains geometric as well as functional details about the component that needs to be imported. Through the XML files, designers need to provide features provided in the manufacturers' datasheets, such as dimensions, name, pin locations, pin types, pin functions, pin compatibility, and names of other components required for basic functionality. The XML file is then interpreted using JavaScript, and the 3D components are created using the three.js [80] library. The system generates a base of the component and renders the pins as children objects of this base. The pins information is obtained from the XML file, which provides the pins' location and the functionalities to assign a color to each pin. FabHandWear presents seven-pin options that are identified in the tool with colored pins to assist the user with the connections. Each color represents one type of pin connection (Digital IO, Analog (ADC), capacitive touch, SDA, SCL, Power, ground).

4.3.1 Adding New Elements . The tool currently has eighteen elements in the components database (4 parametric), which provides a significant number of combinations of sensing, power, and logic. However, we recognize that all designers are different, and requirements may vary across users. Therefore, we enable designers to add more elements that might be more suitable for their vision—gradually increasing the capabilities of the tool.

Adding new components on a web-based system will ensure sharing across users, which means that a component only needs to be added once and accessed by all the users in the future. The number of components will gradually grow, allowing more users to access new technology.

The protocol that adds new electronic components to the tool uses the same XML file, as previously described. The process has the advantage that uses a simple text editor to create the data file. The features are named tags, and each tag represents a characteristic of the tool that allows classification, interconnections, and additional properties. To facilitate the implementation, we share a template of the XML file of one of the elements as an attachment.

4.4 Circuit Routing

After placing the electronic components over the 3D hand model, the tool overlays the position of the electronic components on top of a 2D grid as shown in figure 4b. We make the users place all necessary electronic components on the mesh model before auto-generating connections among them. The users can modify the contour of the connection lines between each of the circuit components if needed, as long as the rendered wire does not intersect or overlap with any other wire and the two endpoints are connected to the pins of the electrical components. The user clicks on the first colored pins to perform this manual operation, followed by the end color pins. The tool does not allow the user to connect pins of different colors (types) as assistance to reduce the errors. Allowing more flexibility to the tool and not constraining the users [54, 89].

We use a pathfinding algorithm over the 2D grid to identify the desired connections [20]. The initial and the final pin conditions are obtained from the XML information, along with the position information of the components. Then the system initiates a search to identify the connections. Grids are side-steps to the next column or row lane (moves to the next available grid). If a path for another pin was established along a particular grid line, the user receives an error alert. On the other hand, if there is no desirable path, the users receive a notification to modify the component location and re-try. Finally, if there are no errors or warnings, the system renders the resultant paths back on the 3D mesh model (projected via ray casting) to be verified by the user.

4.5 Substrate Creation

A substrate is the base material that holds the components of the wearable. The users can create the open shape of the substrate in FabHandWear, which facilitates the fabrication of a conformal 2D wearable. We allow the user to create the substrate contour after circuit traces creation over the 3D model of the hand.

FabHandWear tracks the user's clicks and renders the substrate boundary between two consecutive clicks, allowing the user more control over the overall desired shape of the substrate during fabrication. Once the substrate boundary has been created, we project the boundary onto a 2D surface via ray casting [23] to enable the design to be manufactured via traditional methods.

The substrate satisfies three main conditions to enable fabrication. 1) The substrate always has to keep an open form factor, which means that the substrate on either side of the hand can be connected only via one or the other side of the hand (Across the thumb or little finger). 2) avoid finger joints where the skin stretches, and 3) use V shaped Cuts to avoid the buckling effect in the internal part of finger joints where the substrate will bend.

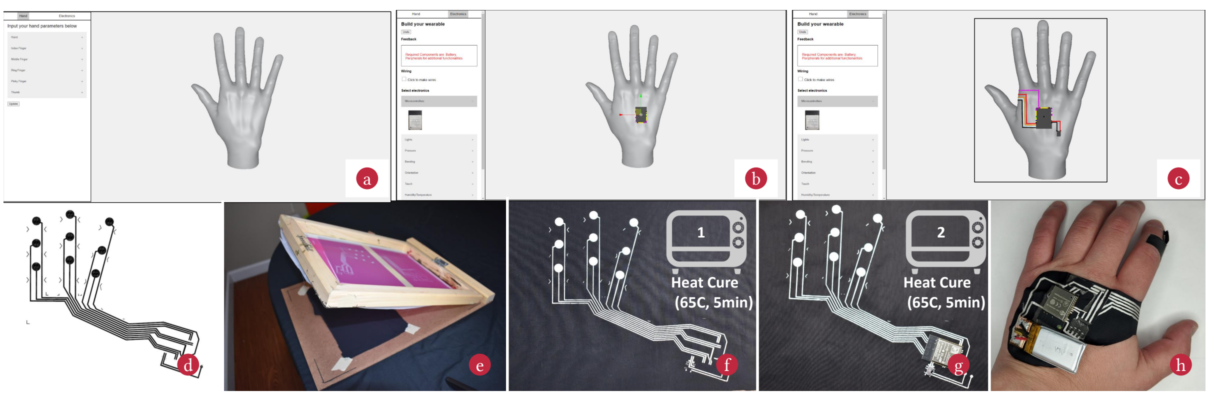

Fig. 5. Design and Fabrication Workflow: (a) Hand measurements parametrization, (b), Place desired components on the 3D handmodel, (c) Generate circuit wires (manually or autorouting), (d) generate and Print the template, (e) Screenprint circuits on nylon fabric using conductive silver ink, (f) heat cure the ink, (g) Assemble components on the circuit and heat cure the connections, (h) Hand wearing the prototype

5 FABRICATION WORKFLOW

Our fabrication process uses commercially available materials and a simple methodology that allow designers from multiple fields to access the proposed manufacturing process [35]. The materials for textiles and circuit traces were selected based on weight, thickness, compatibility, aesthetics, and manufacturability. We leverage from previous work, FabHandWear uses conductive ink to create conductive traces as the core material thanks to its high conductivity and thickness. The ink selection defined the properties needed in the textile substrate.

5.1 Fabric Substrate

The substrate isolates the skin from the circuits, provides a robust base to hold the electronics, and allows the wearable to be reusable. We base our decision on previous experiments that show how inks are not always compatible with any substrate unless the textiles are exposed to special treatments [29]. Based on the ink properties, we select conventional from a conventional textiles list and inks to evaluate the best compatibility. The selection of the substrate required a textile thin, lightweight, and with minimum space between fibers. Stretchable materials and polymers were not considered part of the options due to the cost, fabrication complexity, and properties that were not crucial for our implementation.

Commercially available, the best option we found was a waterproof 100% Nylon (♯6059 Water Repellent 390 T Nylon) from Good Rich Textiles International. To shape the substrate, we print the design template over the textile using any conventional laser printer. The printed template helps for positioning traces and electronics on the fabric and has a contour reference to cut the final shape of the wearable.

5.2 Circuits Traces

The functional part of the wearable uses commercially available electronic elements and thin conductive ink-based circuit traces. Conductive inks are highly conductive, easy to apply, and lightweight [61]. From all the commercially available silver inks, we selected the CI-1036 in from Engineered Conductive Materials [77] because it provides high conductivity, flexibility, and short curing time. The main difference with other inks in the market is that it is not an acrylic lacquer. Acrylic lacquer based paints can dry at room temperature and are prone to crack when a substrate that holds them is deformed. CI-1036 silver ink needs a heat curing process and also allows some flexibility when deposited on textile substrates.

To interconnect the electronic elements, We start transferring the circuit traces to the textile. Using the printed template generated by the tool, we fabricate a screen to screen print the silver ink and create the circuit traces [77]. The advantage of this process is that it can create all the traces precisely in a single pass. It is a fast process and enables repeatability. Once the ink is screen printed over the textile – we proceed to the curing process. The silver ink needs heat to achieve optimal conductivity, so we place the textile with the silver ink traces for 5 minutes inside a toaster oven preheated to 65°C. After curing time finishes and the textile cools down, we use electrically conductive double-sided tape [2] to connect and fix the electronics to the circuit traces. Then, we place the electronic elements to complete the circuit. The electrically conductive tape (z-tape) has two functions: 1) hold the electronics to the substrate, and 2) provide the first level of connectivity between the traces and the electronics. To ensure a robust connection between the circuit and elements, we use a thin brush to paint with silver ink the component pads with the traces. Finally, we put the wearable to cure one more time in the toaster oven (5 minutes at 65°C). As an additional feature, to protect the circuits better from dust or water, we suggest adding a layer of liquid bandage that is flexible, waterproof, and inexpensive.

After the circuit is assembled and fully cured, the user cuts the substrate with scissors through the contour reference lines—our fabrication process aids in making the glove minimalist and unobtrusive. Using conductive paint and z-tape to make flexible, wire-free electronic circuits on a textile substrate dramatically reduces the size and makes the fabrication possible for any user.

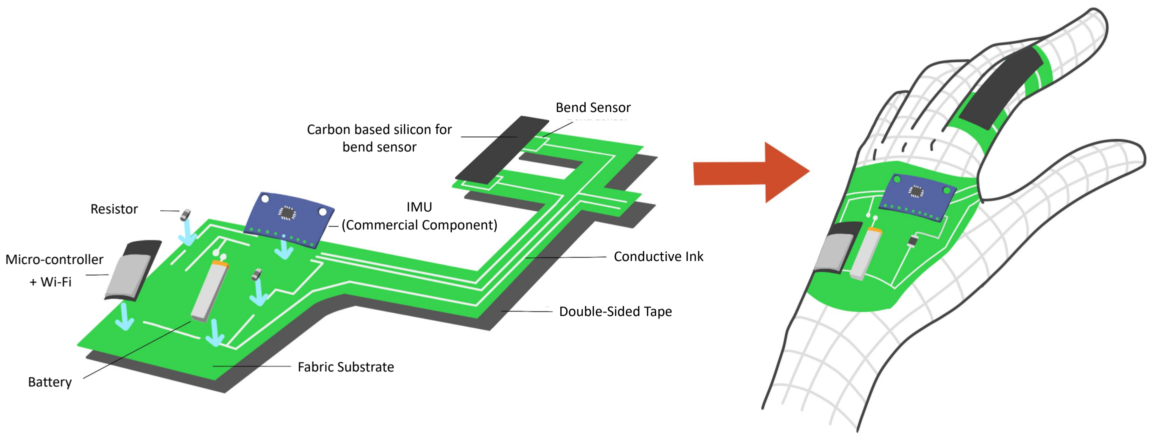

Fig. 6. FabHandWear System characteristics

5.3 Skin Adhesives

To attach the flat wearable glove to the hand (Figure 6), we place the glove over 3M 1509 double-sided tape [3]. We suggest 3M 1509 tape because it is useful for medical purposes, skin-friendly, and adhesion lasts for several days before needing a replacement. We select the best adhesive after comparing it with the other two adhesive tapes commonly used for fabrics and clothing. MIILYE Dress Body double-sided tape, and 3M 1522 clear tape [1, 56], which are as good as the recommended, but they can only sustain a day.

6 EXAMPLE APPLICATIONS

For this section, we selected four different designs to demonstrate the feasibility and applicability of FabHandWear. By allowing users to design on a three-dimensional interface, the design becomes easier to visualize and implement. We will demonstrate the fabrication of a variety of functional applications and customization of hand wearables. We built the models over different hand features to illustrate why hands need a special treatment compared to other parts of the body. Inspired by real-world, health, aesthetics, and sci-fi applications, we show customized hand wearables to monitor health, cosplay, or interactions with emerging technologies.

6.1 Hand Repulsor Prototype

FabHandWear provides a platform to create interactive customs and theatre hand wearables. Inspired by sci-fi applications for theatre, cosplay, performances, and movies, we create a hand repulsor simulated by some RGB LEDs and capacitive touch input for activation. We demonstrate with these applications that they can also develop applications for recreation and artistic purposes to ideate and push creative boundaries. The design uses eight RGB LEDs, a microcontroller, and a parametric capacitive touch sensor. Based on the touch interaction with the sensor, the repulsor will change the light display and the colors (Figure 7a).

6.2 Temperature and Pulse Wearable Meter

During this pandemic, a wearable can provide information to the wearer and the people around them. To demonstrate the integration of a hand wearable with conventional electronics, we implemented a hand wearable that measures body temperature and heart-rate. The wearer measurements are visible on the hand using a pair of RGB LEDs. The output will keep people around informed concerning the current temperature. Temperature is an important symptom that can help for the social distancing of possible infected people. The wearer needs to stick the wearable to the hand to start displaying the measurement. One of the LEDs will display the heart-rate frequency on white, and the other will use a traffic light pattern to display three levels of temperature. It uses green, blue, red, and it ranges from normal temperature to fever. The design uses an ESP32 microcontroller that processes the data collected, Pulse Sensor Amped for heart rate, and a BME280 for temperature measurements (Figure 7b).

Fig. 7. (a) Hand Repulsor (9 components) (b) Pulse and Temperature sensor for constant monitoring (6 components), (c) Nine keys capacitive touch keyboard (11 components), (d) Piezoresistive touch input for Augmented and Virtual Reality (10 components)

6.3 Capacitive Touch Keyboard for AR and VR

We build on the text entry limitations that emerging technology such as Augmented Reality (AR), Virtual reality (VR), or smartwatches present [34, 70, 95, 98, 99]. We present the design and implementation of a text entry hand wearable. The system uses nine capacitive touch input sensors that will allow the user to type words using one hand. The capacitive touch sensors have different geometries that the user can personalize. Therefore, to interact with the designed Keyboard, each sensor enables access to three to four letters organized alphabetically from top left to bottom right. The user has to touch the sensor several times according to the position of the letter. This interaction stimulates the keyboards of one of the first cellphone generations. The keyboard implementation demonstrates how the system can create a network of distributed sensors around the hand (Figure 7c).

6.4 Piezoresistive Thumb-Index Interaction

Leveraging on the previous example, the interactions on AR, VR, and smartwatches menus are cumbersome and very repetitive. Mid-air gestures have shown that they can do the work, but at the same time, they are complicated and exhausting [33]. In the same way, touch inputs on small screens create visual obstruction and create errors when navigating across the options. The Current design example enables directional interactions using four pressure sensors located on the index finger. (Figure 7d) shows the setup to use thumb-index interactions to complete the desired input. The template uses the most reachable area of the index finger [39], so the wearer can press and hold the buttons created, which can enable eight different input modalities. The fabrication of the four pressure sensors used interdigitated electrodes available in the library of components and a piezoresistive layer (Velostat 0.4mm thick). The current application demonstrates how simple interactions can benefit more advanced technologies and illustrate how FabHandWear enables design in any surfaces of the hands.

7 USER EVALUATION

We evaluate our tool's usability with a remote user study, where we asked participants to design three models using FabHandWear. A group of 13 participants (6 Female, 7 Male, 46.15% non-technical background) age between 23 to 35 years old (mean 26.23, SD 3.02) [52] took part in the experiment and were selected through a recruitment email. The participants did not require special knowledge of wearables, design, or engineering. We hypothesize that participants will be able to implement the task using FabHandWear features in a simple and faster way than doing it with manual procedures.

7.1 Study Procedure:

After a project introduction and instructions, the participants start a 10 minutes training session with the system. During the training, the users interact with all the features provided and asked questions about the system and the way it works. The participants had to design three different models (tasks) using FabHandWear.

The tasks had different configurations, components, and hand locations to place them. Task one had three components located on the hand's backside (microcontroller, 2 LEDs from an LED strip, and a battery). Task two used the back of the hand and the palm - it had 4 component types (microcontroller, battery, parametric capacitive touch sensor, LED strip). Finally, the third task used both the back of the hand, the palm, the middle finger, and the index finger - it used five component types (microcontroller, battery, two parametric bend sensors, two resistors, and an IMU). The tasks were balanced across users by using Latin Square Design [7].

We provided the tasks as images of the wearables describing the functionalities and components required for each scenario. In the instructions, participants start by measuring their hands and enter the measurement values into the interface to parameterize the hand model. The next step was to search the menu components, select, and place them over the hand. Finally, the participants manually create the circuit routing to implement the functionalities required. We select the manual routing for the evaluation to allow the participants to use all the tool features.

We record the participants' screens during the test to collect the process and time spent on each task. Each design and the result will depend on how the participants locate the parametric 3D hand model elements. Finally, at the end of the study, the participants complete a post-survey that included System Usability Scale (SUS), NASA TLX, and open questions about the design process [5, 28].

7.2 Results and Discussion

All the users were able to complete the three tasks. Considering the variety of backgrounds and the inexperience in developing wearable devices, the participants reported a mean raw NASA task load index (NASA TLX) score of 47.5 (SD=15.083) [9], and a mean system usability score (SUS) of 70.42 (SD = 16.61), ensuring the usability of the system. From the observations and the participants' comments, we were able to identify how the participants improve the performance during each task.

In particular, participants were satisfied with the tool and the benefits it provides. They all agree that being able to design over the 3D interface simplifies the wearable concept and design. Suggesting that the flexibility adjust the wearable to the hand and tailored to their needs relieves many of the wearables design workload.

Table 1. The average time spent during the design tasks with FabHandWear.

	Task 1	Task 2	Task 3
Average time [min]	19.96	16.57	16.19
SD	6.64	3.31	3.85

Figure 8 illustrates the hands of three of the participants wearing one of the templates that resulted from the test. The users selected were the ones located in a close location to the team. The differences in the hands were independent of the height and sex of the users. Hands are unique in proportions; for example, a female participant on Figure 8a had longer fingers than the male participant on Figure 8c. However, the width of the palm of Figure 8b is larger than Figure 8a, which reflects the variability of hands and how important is the size personalization on hands wearables [44, 69].

The simplification allows users to focus on the functionality desired. Increasing the trust in designers with no engineering or technical backgrounds and allowing more exploration of applications. We envision many artists, dancers, and musicians will be able to prototype new forms of interaction. The results and the observations during the user evaluation showed how the users were faster after each task (Table 1). The time reduction was independent of the task complexity and the number of components.

In general, participants found the feedback assistance helpful and necessary for users with no engineering backgrounds to avoid negligent mistakes (11/13 participants, comments). The participants also suggested that it will help if the assistance message appears closer to the component and provides more description of the selected component. Additionally, participants commented that the components menu was beneficial and organized (10/13 participants). They found it faster to search for components by categories and with the actual picture. We can attribute part of the time reduction to the components menu. Once the users became familiar and comfortable with the system, the next tasks focused on completing the assignment and not on searching components and navigating the menu. When the knowledge of components currently available and the ones that are very day added to the market, the menu classification based on its use/functionality becomes a link that will open hand wearables to other types of designers. The remaining participants found it adequate but suggested expanding the electronics library. Three participants agreed that the snapping feature between the component and the 3D mesh surface was helpful. A participant stated that the overall effort to use the system was just as easy as creating an

Fig. 8. Users fitting results of one of the hand wearable customization patterns. Illustration of the differences of hand features across users with a fitted design.

electronic printed circuit board (PCB). Another participant motivated by the task suggested "the integration with actual 3D printing," promoting future thinking and creativity in the system.

Our system structure enables access to the design and fabrication at any location. Users do not need to use special machinery, clean rooms, or tools to obtain a functional prototype, which previously was found as limitations when users with no technical backgrounds design their personalized hand wearables [24, 54, 69]. Therefore, the accessibility, low-level entry barrier, and community shared library contribute to create a solid base to scale the system and allow the multidisciplinary prototyping perspective.

By analyzing the feedback, We notice that almost all participants agreed that simplifying the manipulation method for smaller components and a tutorial video will positively improve the experience. Components such as resistors, LEDs, capacitors are significantly smaller than the rest of the components and have different interaction types. Additional comments suggested adding a simulation engine to test functionality before fabrication and providing feedback during circuit creation would add value to FabHandWear.

The system's overall acceptance was evident when asked the participants to suggest what they would like to prototype with the system. They reported wearables for diverse application areas such as gaming controls, water trackers, hand tracking wearables, smartphone interactions, AR/VR, and IoT interaction.

8 LIMITATIONS AND FUTURE WORK

8.1 More Inclusive Parametrization

FabHandWear currently supports the design of hand wearables on a parametrized five-finger hand structure. We want to explore the possibility to make our method more inclusive to multiple audiences. We are planning to add controls for additional physical characteristics such as extra/fewer fingers.

8.2 Circuits

currently, the system supports one layer circuits and adds a second layer manually (power lines or voltage dividers). We plan to improve the current circuit algorithm to allow multiple layers and keep the 3D design functionality without affecting the user experience. An additional layer will provide flexibility to increase the number of components on the designs and increment complexity. We are currently working on implementing these features using an alternative manufacturing process that will assist users with the fabrication and assembly process to control multiple materials that are out of the scope of the current work.

8.3 More Advanced Users

The transference of circuit traces using screen printing enables accessibility and precision during the fabrication. We are currently adding features that will allow modern fabrication technologies such as material deposition machines (3D printers) for more advanced users and applications. These will enable us to fabricate electronic components directly on the substrate.

8.4 Waterproofing

Current hand wearables can be water-sealed using liquid band-aid, but this procedure is only temporal. Methods that can allow fast and easy sealing of the electronics without affecting the wearability should be explored.

8.5 Real Time Optimization

Current design implementation present textual and visual cues that assist users during the process. We are currently working on an optimization algorithm that allows users to obtain the components' distribution based on geometrical and electrical constraints in real-time.

8.6 Actuators

Currently, the system only supports one type of vibration motor. However, the exploration of how to adapt new forms of actuation is under exploration. The process is undergoing along the lines of adding deposition methods in the process.

8.7 System Distribution

As mentioned in *Section 4*, FabHandWear was build by using a web-based format. The system will use a free-content format open to all the users. FabHandWear will use an identification system to log in and be able to save designs, add new components and share content across the community. We want to create an environment where everybody can share content and contribute to the community. We will implement the login and identification feature to avoid disruption of the database of new elements.

8.8 Personalization and Reachability

To understand the impact of the tool in terms of personalization capabilities and practical functionality, we are planning to test the design volume and variety of hand wearables. We want to understand the difference in ideas, needs, and user capabilities when exposed to practical applications. A remote workshop that will require synchronizing time zones and the distribution of materials is considered the best alternative. The workshop development process will help us reflect on the system capabilities and new options to evaluate wearables remotely. Additionally, we will be able to identify a greater variety of applications of users with different backgrounds. For example, actors could create their hand wearables as part of their costume to control features of the scenes during acting, or a material science engineer who would like to test the applicability of a new sensor to collect object grasping data [24].

We believe that FabHandWear offers the possibility to prototype wearables for more complex body parts and enable the new generation of seamless hand wearables. We want to explore this as part of future work.

8.9 Conclusion

We introduced FabHandWear, a complete end to end design and fabrication system to develop self-contained functional hand wearables, enabling multiple levels of customization of shape and functionality. FabHandWear enables accessibility to makers to encourage exploration and applications of new forms of hand wearables. We envision an emerging generation of customizable hand wearables that support hand differences and various functionality, and our method will open up this space for interaction design and new possibilities. The design of a 3D parametrized hand enables us to control hand measurements and the perfect location of electronic components, which benefits the fit of the resultant wearable. The design tool ensures that the final wearables can be functional after fabrication. The simple fabrication approach allows wearables to be fabricated with relative ease and minimal experience, empowering a DIY approach. We fabricated five hand wearables as potential use cases, conducted a technical evaluation and a user evaluation to demonstrate the ease and potential of FabHandWear.

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