WovenProbe: Probing Possibilities for Weaving Fully-Integrated On-Skin Systems Deployable in the Field

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ABSTRACT

On-skin interfaces demonstrate great potential given their direct skin contact; however, conducting field studies of these devices outside of laboratories and in real settings remains a challenge. We conduct a *research-through-design* investigation using an extended woven practice for fabricating fully-integrated and untethered multi-sensor on-skin systems that are resilient, versatile, and capable of field deployment. We designed, implemented, and deployed a woven on-skin index-finger and thumb-based inertial measurement unit (IMU) sensing system for multi-hour use as a *technology probe* to understand the social, technical, and design facets towards moving integrated on-skin systems into a wearer's daily life. Further, we integrate a woven NFC coil into the IMU on-skin system, which is wirelessly powered by a smartwatch substitute, signifying the potential of our woven approach for developing wirelessly powered on-skin systems for longer-term continuous wear. Our investigation and the lessons learned shed light on the opportunities for designing on-skin systems for everyday wear.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

On-Skin Interface, Weaving, Fabrication, Gesture Tracking, Field Deployment, Wearable Technology

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1 INTRODUCTION

On-skin interfaces [39, 51, 77, 79] have emerged as a promising new form factor for wearable devices. Due to their direct contact with the body surface, they serve as a window to the rich information of a user's activities and needs. As sensor devices become increasingly miniaturized, on-skin interfaces are projected to have an impact on applications ranging from pervasive healthcare [42], the future of work [3], to improving everyday user interactions [78].

While Human-Computer Interaction (HCI) research has developed approaches for the user-friendly fabrication of on-skin interfaces, to date, conducting field studies of these devices outside of laboratories and in real settings has remained a main challenge. This limits the potential of these interfaces to make a direct impact in daily lives. The main challenges in conducting a field study are (1) the lack of a suitable sturdy substrate that can be worn for extended periods without being bulky, and (2) limitations in integrating an array of miniaturized printed circuit boards (PCBs) — which are critical for sensing and computation — effectively as part of the on-skin system. While film-based approaches, which are made of flexible and stretchable materials such as silicone and polyurethane [39, 78] stacked in layers, are more common for on-skin interfaces in HCI [38, 39, 76], current approaches still often lack in the sturdiness and stability to withstand regular wear and tear for longer periods. Garment-based textile fabrication approaches (e.g., woven e-textiles) [13, 66, 70], on the other hand, can provide a sturdy yet slim substrate that can remain unaltered after extended use. Textiles are wearable by nature yet can be very robust and strong, making them particularly interesting alternatives for on-skin interface applications.

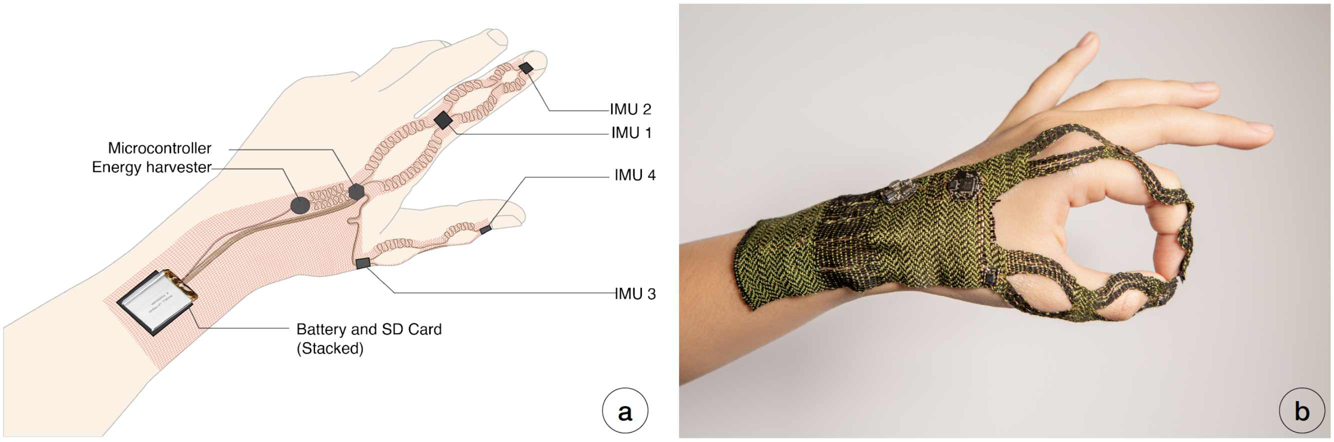

Figure 1: (a) Layout of the WovenProbe, an index-finger and thumb-based inertial measurement unit (IMU) tracking system explored in this paper. It includes a woven bandage-like interface that supports complex on-skin circuitry: four IMUs on the tips and ends of the thumb and index finger, a central microprocessor, an energy harvester, a battery, and a SD card. (b) Implementation of the system.

Weaving, in particular, has several benefits for fabricating resilient and versatile traces for on-skin interfaces. In this work, we conduct a Research through Design (RtD) investigation in the potential of using the craft of weaving for fabricating fully-integrated on-skin systems capable of being worn in a real setting. Due to its unique interlacing structures between two distinct sets of yarns, weaving allows organized trace routing for easy integration of distributed PCBs while providing the option for versatile circuit topographies. Furthermore, different woven structures can be merged in a single interface to offer support to the wires in regions with electronics and increase conformity at body landmarks that require flexion. In addition to its functional benefits, weaving can also bring richness in the aesthetic and cultural expression into on-skin interfaces, providing an avenue for solving some of the major challenges of developing fully integrated and durable on-skin systems.

Using our developed approach, we conduct a field study in which we deploy an integrated woven on-skin system as a *technology probe* [33, 35] to understand how a fully-functional on-skin system might fit into a wearer's daily life. Our fully-integrated "probe" consists of over 20 wires which connect 7 miniaturized PCBs on the challenging body location of the hand through a woven substrate. The probe was worn continuously by the wearer in a real setting for 6 hours, in which over 10 million data points were collected on the wearer's activity. Through the technology probe, we gather insight on the social aspects towards device usage, the technical aspects of engineering on-skin systems for field studies, and the design aspects for the research design of future systems.

To further demonstrate weaving's versatility, we integrate an Near-Field Communication (NFC) coil into an on-skin system as a case study of wirelessly powering on-skin systems for extended continuous wear. More specifically, we use woven technique to integrate on-skin system with near-field-responsive inductive patterns that are capable of receiving power from a smartwatch substitute through radio-frequency identification (RFID).

We make the following contributions in this paper:

- We introduce WovenProbe, a fabrication approach using an extended woven practice for generating a fully-integrated on-skin system. We contribute novel weaving techniques under-explored by prior works for a sturdy, versatile, and slim substrate, including lace serpentine weave which provides skin conformability for diverse body landmarks, and complex weave designs for creating free form patterns such as inductive coils.
- We conduct a multi-hour, continuous-wear study of a fully functional on-skin system fabricated with the woven approach. The on-skin system serves as a technology probe for eliciting social, technical, and design insights on developing on-skin systems capable of field deployment.
- The case study of WovenProbe (Figure 1) in a index-finger and thumb-based inertial measurement unit (IMU) tracking system integrated with an NFC coil for wireless charging and data transfer.

2 BACKGROUND AND RELATED WORK

2.1 Textile Fabrication Processes

Researchers in HCI and wearable computing have integrated input sensing [16, 41, 47, 60, 63, 64, 68, 89] and output actuation [26, 45, 81] into fabric forms. Fabrication processes include *surface level integration* of interactive elements through stitching [15, 65], embroidery [6, 24, 25, 28, 30, 61, 89], machine sewing [57], felting [10, 34], silk-screening [43], and inkjet printing [86]. While these methods can rapidly augment a textile, they alter the textile only in an extrinsic manner. We aim to alter the textile structure itself to fine-tune its properties for on-skin application.

Weaving [13, 17, 20, 23, 66] and knitting [7, 26, 62, 80] afford *structural-level integration* of interactive elements at the yarn-level. Weaving intersects two sets of yarns, held under fixed tension, in perpendicular directions on a loom. This structure allows for fine control of tension to incorporate delicate electronic components and thin materials, which are less likely to withstand the higher tensions of knitting's continuous loop-to-loop structure. While knitting is often preferred for stretchable textiles worn close to the skin, weaving's structural qualities and lack of restrictions for materials make it the favored method for structurally integrated smart textiles — from integrated circuits [13, 19, 20], to touch surfaces [64, 66, 83, 91], to morphing interfaces [73], to textile displays [11, 17, 18].

In this work, we introduce under-explored weave structures and techniques suitable for fully-integrated on-skin systems. Closest to our work is WovenSkin [70], which provides a generic fabrication process for woven on-skin circuitry. While WovenSkin introduces some multi-layer circuit topographies, it does not address the integration of distributed PCBs into the woven substrate. Further, WovenSkin develops weave structures for planar (flat) body locations and does not address the challenges involved with creating traces for flexible body locations (e.g., joints), which are critical for applying fully integrated and untethered systems on the skin. In our work, we introduce hand manipulated lace weaves [4] which can be employed for localized flexibility, and altered tapestry and double weaving techniques not introduced in WovenSkin for the versatile layout of the complex circuit components. Taken together, this provides a versatile vocabulary for fabricating the diverse types of trace routing required for a fully-integrated on-skin system.

2.2 On-Skin Interface Fabrication Processes

Material science research on epidermal electronics has demonstrated electronic circuitry that matches the properties of skin [42]. However, these advanced capabilities entail high cost and manufacturing challenges, limiting them to advanced labs [9]. To broaden access, the HCI and wearable communities have explored user-friendly and inexpensive fabrication processes to create on-skin interfaces. Interaction modalities include input through capacitive touch [39, 52, 59, 78, 79]; output through thermochromic pigments [39, 40, 77], haptic feedback[29, 82], and stiffness change [37]; and sensing through IMUs [38, 54], strain sensing [52], and biosensing [58, 85]. These interfaces are fabricated using different *film-based* approaches, including lamination [54], laser-patterning [78], and screen-printing [52, 59, 79, 82]. However, these film based approaches (e.g., duoskin [39], skinwire [38]) are often limited in their ability of generating more diverse circuit topographies (vias or coils), stretchable interfaces, and they are not often mass producible, making them an unattractive option for fabricating complex and flexible on-skin circuitry on a large scale towards field deployment.

Orth [61] and Molla et al. [56] have discussed the advantages of *yarn-based* structures, which can be inherently body-conformable, as alternatives to the current dominant film-based approaches to soft interfaces. Weaving presents a rich platform for versatile circuit topographies, affords scalable manufacturing, and offers creative exploration, providing unique advantages over other silicone based approaches. WovenProbe builds on this insight, blending yarn-level woven structures for resilient on-skin interfaces. Further, while there have been efforts to generate fully untethered on-skin systems [38, 54], most research excludes the power and data unit from the skin interface. While often not described in detail, in practice, they are external, rigid units connected as add-ons to the on-skin devices, limiting long-term wearability. WovenProbe combines the advantages of complex circuit topographies (e.g., [70]) and integrated distributed PCBs (e.g., [38]) with the additional benefit of novel woven techniques for on-body systems.

In this paper, we leverage the resilience of textile weaving to generate sturdy and versatile on-skin circuitry with distributed PCBs and interfaces that can be worn for longer periods. In addition to rigid PCBs, the wires, which enable the sensors to precisely contact the body, must be integrated into a slim form while being robust under movement. Moreover, connecting multiple wires requires methods to manage the complexity by grouping or stacking the wires elegantly. We blend on-skin interface fabrication with weaving technology as the linear nature of weaving provides tenacity and organizational patterns to stabilize these complex wiring structures. Specifically, we exploit the unique interlacing structures of weaving for organizing trace routing for easy integration of distributed PCBs while improving conformity at body landmarks that require flexion.

2.3 Studying Wearability of On-Skin Systems Deployed in the Field

Current evaluations of on-skin interfaces focus on in-lab bench tests. In-lab bench tests provide quantitative data of device performance under a controlled setting. However, they fail to uncover: (1) the effect of everyday activities on a device, (2) the social perceptions towards device usage [21], (3) the performance of the device when worn on human skin (versus silicone replicates in bench tests [39, 78]) for extended periods, and (4) the effects of body geometries (e.g., knuckles) on the device. These factors can only be explored through field deployments.

For emerging and novel technologies such as on-skin interfaces, it is critical to understand how people interact and perceive these technologies in a social context [67], and the type of improvements required for these technologies to mature and be integrated into people's lives [50, 87]. At the same time, it is also important for on-skin interfaces to remain fully functional after extended wear. The performance of a fully-functional and fully-integrated on-skin system thus far remains under-studied. The main challenges lie in the devices being early prototypes that require constant recharging due to current battery limitations and substrates that are delicate and easily breakable, making them difficult to deploy beyond controlled tests [38, 39]. Closest to our work is the study conducted in SkinWire [38]. However, it is important to note that the prototype used in the SkinWire study is non-functional. Instead, it uses 3D printed stand-in components to represent the PCBs and battery. To more realistically understand the effects of a system worn in the field, we contribute a study in which participants wear a fully-functional system throughout a multi-hour period while continuing with their daily activities. We deploy and evaluate our WovenProbe system in real settings through a lens of *technology probe* [33, 35], a technique for understating the usage of early technologies in a real setting.

Technology probes [33, 35] are early but high-fidelity prototypes, often deployed in a real world setting, as a prompt to help people see how a new technology or a new application might become a part of their day-to-day lives. They help users and designers in eliciting the technical, design, and social aspects of a novel system in an real setting with "the social science goal of understanding the needs and desires of users in a real-world setting, the engineering goal of field testing the technology, and the design goal of inspiring users and researchers to think about new technologies." [35] While there is an element of risk in deploying probes (probes can fail or bring unexpected results), they can still generate some useful design insights which might not be achieved using traditional evaluation techniques. It is the aim of this work to fabricate an on-skin system capable of being deployed as a "probe", which requires improvements in substrate durability, power management, and firmware robustness. We deploy our woven on-skin system as a technology probe [33, 35] for eliciting insight of the system in a real context [33].

3 WOVENPROBE: WEAVING A FULLY-INTEGRATED ON-SKIN SYSTEM

We are motivated to develop a fabrication approach which can accommodate the diverse needs to translate a fully-functional system onto the skin. To achieve this, we adopt a research through design [90] methodology where we conducted extensive design experiments with the woven craft, tested each iteration worn in an everyday setting, and iterated for improvements. We synthesize the following design objectives and fabrication approach through the research team's one-year extensive weaving experiments, consultations with professional weaving experts, and literature review on advanced yet under-explored weaving techniques [1, 4].

To demonstrate and ground our weaving fabrication approach, we will use an example of an index-finger and thumb-based IMU sensing system (Figure 1). This example highlights both the limitations of conventional approaches and the challenges we overcome with our work. Hand gesture recognition has great potential in many applications such as augmented reality [22], sign language recognition [74, 84], and robot control [32]. While tracking the fingers provides a rich context of user interactions, fingers require high dexterity and offer limited space to place components. We create a system that uses IMUs to track the thumb and index finger's motion: IMUs are attached to phalanges of the hand where the orientation is established. The sensors are placed on the distal phalanx and metacarpal of the thumb and the index finger's distal and proximal phalanx. The IMUs are then connected to a microcontroller, which can either be powered by a battery or wirelessly receive power and transmit data through RFID via a pod-like device (smartwatch). Here we introduce our fabrication approach for weaving a fully-integrated on-skin system.

3.1 Design Objectives

We extend weaving techniques under-explored by other works to fabricate fully-integrated, durable, and versatile on-skin systems. This includes lace-weaving for conforming to diverse body landmarks, seamless integration of spatially distributed electronic components (custom-fabricated PCBs) into thin woven interfaces, and techniques for weaving complex functional elements (e.g, coils). Figure 2 describes the design strategies we implement for the WovenProbe, supporting both battery- and wirelessly-powered systems.

- **Versatile structural topographies for flexion in the wrist region and around the knuckles (Figure 2-b1, closeup c1):** Weaving offers both structures that are highly durable, providing additional support to integrated PCBs, as well as structures that are slimmer and more flexible, for increased compliance at body locations with challenging curvatures or which require flexing. Different from traditional weaving, where the warp and weft yarns fully intersect, lace weaving [4], which remains largely under-explored for soft wearable interfaces, *interlaces* sections of warp and weft yarns at non-orthogonal angles to expose regions of negative space and achieve a slim form, making it particularly suited for joints. In WovenProbe, we merge different woven structures in a single interface, tailoring the device to support electronics and conform to body landmarks as needed. We extend a hand-manipulated Spanish lace technique [4] for the wrist and knuckles.
- **Trace routing for integrating distributed PCBs throughout thin woven structures (Figure 2-b2, closeup c2):** The grid-like structure of weaving makes it advantageous for routing groups of wires in a Manhattan routing in both the warp (vertical) and weft (horizontal) directions, mirroring PCB trace design. It is particularly advantageous in WovenProbe for effectively routing a complex network of distributed PCBs throughout a very thin substrate in groups of wires, making the process of translating an fully-integrated electrical design into a slim on-skin form more straightforward and intuitive.
- **Complex circuit topographies (Figure 2-b3.1&b3.2, closeup c3):** Advanced woven techniques such as double weaving, tapestry, and lace weaving enable a variety of 2D and 3D circuit topographies, allowing even greater customization for a variety of systems and their design criteria. Double-woven structures can integrate circuits across multiple layers with vias, while tapestry and lace weaving are used for further manipulation of traces. In WovenProbe, we developed both a double-woven coil with vertical interconnects (Figure 2-b3.1) as well as a slim tapestry coil for RFID charging and data transfer capabilities (Figure 2-b3.2), which have not been presented by other on-skin weaving works. Additionally, we use lace weaving to incorporate stretchable serpentine patterning, commonly adopted for flexible electronics, around the knuckles to increase electrical durability during finger flexion [42].

3.2 4-Step Fabrication Process of Woven On-Skin Interface

Step 1: Sketching. The fabrication process starts with on-body sketching, where the design is sketched onto a stencil overlaid on the body, deciding the electrical layout of the interface on the body surface. We demonstrate with the example of an IMU-based hand tracking system, with the electrical layout in Figure 1a. We adopt a 15-step hand measurement system (detailed in the supplementary document), which is derived from the literature [27] and our iterative prototyping process, for a customized anthropometric fit to the wearer's hand that can withstand and accommodate stretch due to a wide range of hand movements during daily activities. This measurement system is more detailed than methods used to create glove sizing systems [31] as our on-skin device must take

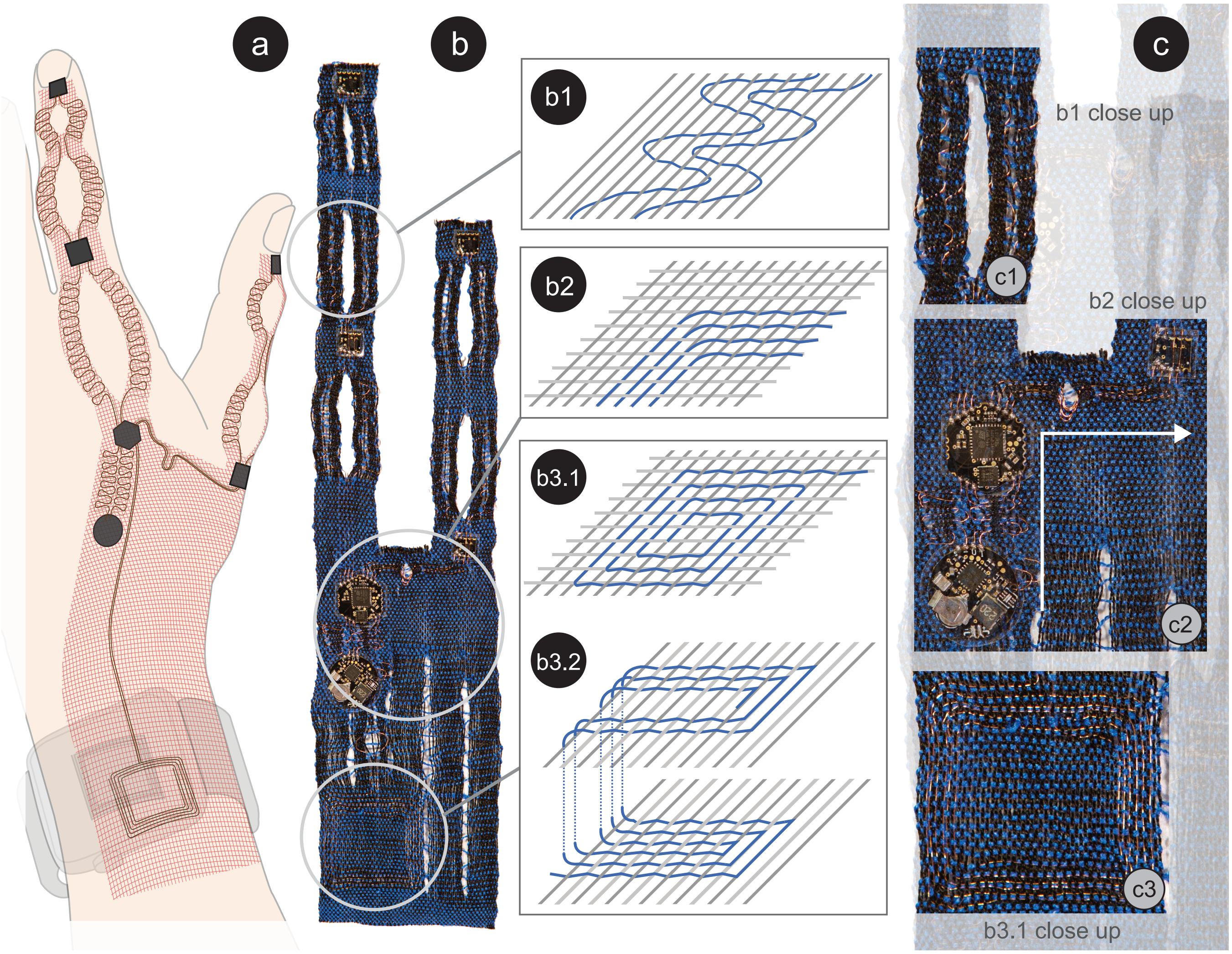

Figure 2: (a) Placement of WovenProbe device on the hand. (b) Weaving technology adopted in WovenProbe: (b1) Lace serpentine, (b2) Manhattan routing, (b3.1) Tapestry coil , & (b3.2) Double weave coil. (c) Close ups of b1, b2, b3.1.

joint curvature into account. The data points collected by way of the measurement system point are used to sketch a custom fabric stencil to articulate the size of the bandage and the placement of components within the bandage.

Step 2: Fabrication of the Woven Traces. We now have a guide (the stencil) of the traces to be fabricated and their respective placements. We use a weaving loom to weave extremely thin yarns and wires into a slim bandage-like interface, which can then be transferred to and adhered onto the skin. We demonstrate our functional example with a combination of weaving technologies that satisfy our aforementioned design objectives and accommodate for movements of the fingers and joint areas.

Weaving Process Overview. Woven fabric is formed by interlacing warp (vertical) yarns and weft (horizontal) yarns, which run in perpendicular directions (Figure 3). The basic woven structure is plain weave, in which neighboring weft yarns pass through warp yarns in alternating sequences to secure the structure. To create more complex designs (i.e., coils), a tapestry weave can be adapted to incorporate weft yarns by manipulating them by hand in specific locations. A lace weave can be viewed as an advanced variation of tapestry weave with deflection in the warp and weft threads to achieve exposed regions. For a comprehensive introduction to the weaving process, please refer to our supplementary document.

Weaving Preparation. In preparation for weaving, we start by drafting the woven interface. We calculate and draft the weaving parameters (e.g., length, width, ends per inch) of the WovenProbe based on the stencil, with the width of the weave matching the width of the wearer's wrist. In this step, it is also critical to identify the specific weaving technology to apply on sections of the weave to account for specific body locations and functionality. We then proceed to prepare the corresponding slim materials (both conductive and non-conductive) for weaving and set up the loom. For the conductive yarn, we use both 38 and 34-gauge electrical wires to transfer data and power between hardware components and for

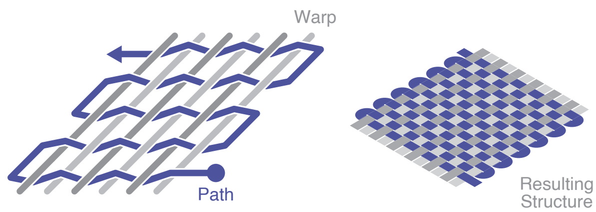

Figure 3: Basic weave structure.

the non-conductive yarn, we use Nm 60/2 silk yarn. For fabricating the WovenProbe samples, we use a Baby Wolf loom with 8-shafts and 10 treadles (Schacht) due to its ability to support more complex designs and structures. Other looms types (table looms) are also suitable. A detailed description of the drafting process and loom set up steps are in the supplementary document.

Structure. Once the loom is set up, we weave the device according to the weaving technology patterns. In our demonstration of an IMU-based finger tracking interface, we weave the device, starting from the wrist and ending at the fingertips, using a combination of plain weave, lace, and double/tapestry weave. We use *plain weave* for structural durability on the majority of the bandage and in areas which are relatively flat and do not contain any joints (e.g., back of the hand). For the finger and thumb joints, we apply *Spanish lace* to manipulate the silk yarn and insulated wire simultaneously to create serpentine traces on two sections that spread around the sides of the joints. Using a fine needle, we weave the excess wire from the serpentine traces into the sections of plain weave to the four IMUs, connecting the components on the fingers. For the remainder of the components housed on the back of the hand, we again use a fine needle to weave wires between the IMUs and the microcontroller (MCU) PCB and between the MCU PCB, the energy harvester, and the NFC coil. To create an NFC tag, *tapestry techniques* can be employed with a fine needle to weave an inductive charging coil into a single-layer weave. For all trace connections, we use 38-gauge copper wire, except for the connection between the MCU PCB and the energy harvester, where we use 34-gauge copper wire due to the reinforcement needed to keep the connection durable and stable in this area.

Step 3: Incorporating Electronics & Insulation. Once the woven on-skin interface is readily fabricated, the PCB islands are soldered directly to the exposed ends of integrated woven-in wires. The PCBs are designed with castellated holes at the edges to conserve space and maintain a flat plane when soldered into the woven on-skin interface. Prior to soldering, the enamel insulation on the wires is mechanically removed via sandpaper. Finally, we coat a thin layer of silicone as an insulation material to protect the PCBs from water and accidental damage during wear.

Step 4: Applying on Skin. To apply the device on the skin, we apply a layer of eyelash glue (DUO Quick-Set Clear False Strip Lash Adhesive) on the entire back of the wrist and we adhere the device directly on the skin. The device can be removed via a a skin adhesive remover (Pros-Aide adhesive remover) on the woven substrate.

4 EVALUATION

We start with wearability study in which we deploy a WovenProbe device as a technology probe [33]. Participants wear a fully-integrated on-skin system for a multi-hour period, from which we elicited insight on the social, technical, and design aspects of designing on-skin system which can be worn in an everyday setting. Based on the findings, we implemented a case study that demonstrates the capability of the fabrication approach to generate a self-contained thumb and index-finger based IMU sensing system which is wirelessly powered via NFC, demonstrating potentials for future longer-term deployment.

4.1 Wearability Study: WovenProbe Device as a Technology Probe

The objective of this study is to understand the wearability of an integrated system fabricated with the WovenProbe approach where our prototype serves as a *technology probe* [35]. It is critical for on-skin interfaces to become a fully-functional system, which we built and leveraged for this study. Our study design focused on ecological validity by testing the devices in the context of everyday wear, in contrast to controlled bench tests used in previous works [39, 78] which are repeatable but do not capture the types of stresses we have in our system. By directly interacting with the device, we hope participants could provide valuable insights about the device which will lead to a better system that will work well in the long run and fulfill the social, technical, and design needs and/or desires of the wearer.

Our technology probes involve developing and deploying a fully functional on-skin finger-tracking device in a real use context, watching how it is used over a multi-hour period, and then reflecting on it to gather information that can inspire new ideas for new on-skin technologies. To more realistically understand the effects of a system worn in the field, participants in our study wear a fully functional system throughout a multi-hour period in the workday and engage in their typical day-to-day activities (office work). Building on research guidelines for technology probes and techniques for evaluating wearability factors of wearable [44, 50, 88] and on-skin [38, 50] devices, we aimed to understand the following key aspects with our WovenProbe:

- From an ***engineering perspective***, we were interested in discovering whether and how long the device can remain functional in a multi-hour use in a workday. More specifically, we were interested in evaluating the *mechanical durability* of the system, i.e., how well does the device remain mechanically adhered to the skin under everyday wear; and the *electrical functionality* of the system, i.e., how long can the on-skin interface remain functional when worn on the wearer's body. The latter refers to the electrical continuity of the conductive materials remaining intact.
- From a ***social science perspective***, we were interested in learning about the needs of the wearer and how they perceive wearing the device in a social context. We were particularly interested in learning, e.g., whether the wearer finds the device comfortable to wear; how does the wearer feel about being viewed when wearing the device, socially; and whether it is personally desirable to wear.

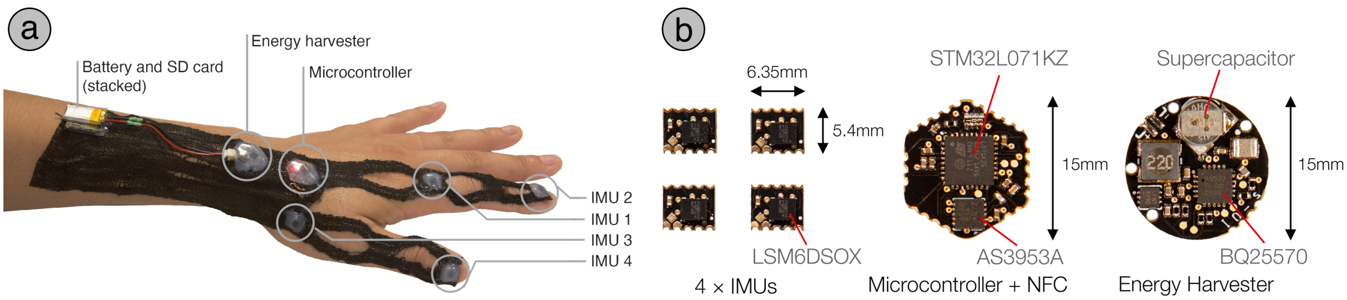

Figure 4: WovenProbe prototype. (a) Apparatus for user study. (b) Typical hardware components used to build our prototypes. Shown here are the version used by the NFC prototype.

- From a ***design perspective***, we were interested in understanding how the wearers perceive the design of custom-made woven device, and envisioned applications for the device.

Our WovenProbe was deployed in 2-stages. Due to the challenges of directly deploying a fully-functional system under COVID-19 social distancing restrictions, we started with a preliminary study with co-authors in our social distancing bubble to iterate on the system. We then deployed the system for a field study by external participants.

4.2 Apparatus for Technology Probe Deployment

Our WovenProbe hardware system includes four IMUs (two each on the index finger and thumb), a microprocessor, an energy harvester (used for power management), an SD card, and a 3.7V, 40mAh LiPo battery (20×11×3 mm) which powers our prototype (Figure 4). The battery connects to the energy harvester, and the data is stored in the SD card.

We intended to select components having small form factors and low power requirements while providing optimum performance for an extended period of time. For the IMUs, we selected the ultra-low-power ST LSM6DSOX IMU which has a footprint of 3mm × 2.5mm and could transfer data through I2C. The relatively large 3kB FIFO in LSM6DSOX allows it to store data for a long period of time without direct intervention from the main MCU. We decided on I2C as the data bus of the system as it is versatile and requires only 2 communication lines.

The MCU PCB consists of an ST STM32L071KZ MCU and an AMS AS3953A NFC transponder. STM32L071KZ is an ultra-low-power MCU that offers two I2C interfaces (one for each finger) and an SPI interface for high speed communications with the NFC interface or an SD card. For the user study, we modified the MCU PCB design by removing the NFC chip and adding pads for connecting the SPI bus to an SD card housed in a separate PCB. This also allowed us to shrink the diameter of the board from 15mm to 13mm. The energy harvesting board, 15mm in diameter, was used as a voltage regulator for the LiPo battery during the user study and output 2.85V to rest of the system.

The firmware was implemented to detect error that could happen during the study and reset the corresponding part of the system (e.g., it would reset a certain IMU if the reading did not match the expectation). Once the battery was connected to the device, a blinking LED indicated that the device was functional and the readings were retrieved from the IMU FIFO and recorded in the SD card. To conserve battery life during the multi-hour study, the MCU was put into sleep mode for most of the time and only the IMUs were active constantly.

All the electronic components were spatially distributed over the wrist and fingers areas to allow ample flexibility to the wearer while maintaining the required electrical continuity between components. Components were directly soldered to the exposed ends of the copper wires integrated within the woven structure.

4.3 Stage 1: Preliminary Study

4.3.1 Apparatus. For the preliminary study, we developed custom-sized prototypes using the data gathered from the hand-measurement survey (as detailed in Section 3.2).

4.3.2 Preliminary Study Procedure and Results. We conducted a preliminary study to test the functionality of the system before the field deployment. Due to COVID-19 study restrictions, we conducted the preliminary study on three co-authors within a social distancing bubble. Each of the co-authors donned and adhered the device on their non-dominant hands for a total of six hours with the battery plugged-in and they engaged in their typical day-to-day activities throughout the study. We primarily sought to understand the engineering aspects of the system including mechanical durability and electrical continuity for iteration before the external study. Our pilot study results showed that the WovenProbe maintained adhesion to the skin over the course of 6 hours for all of our participants, with slight detachments towards the fingertips, wrist, and the areas adjacent to the electronic components. We suspected that repeated movements of the hand caused continuous shearing on the rigid areas adjacent to the components. In addition, the tip of the finger was subjected to catching on objects, making the area particularly vulnerable to detachment. In case of electrical continuity, our best result showed that the device was fully functional after the six hours of study with no major issues observed throughout the process. There were two occasions (out of three) where the device stopped working before the end of the six hours study (e.g., 4.5 hours and 3 hours respectively). After analyzing the data, we found that the main PCB, the energy harvester, and IMU3 were the most vulnerable areas in the device and most of the wire breakages occurred within those areas. We strengthened the wire connections in these areas for our field study.

4.4 Stage 2: Technology Probe Field Study

4.4.1 Apparatus. In our preliminary study, we found that the connections between the MCU PCB and the energy harvester and the IMU3 were the most vulnerable areas and prone to breakage. Hence, for the field study, we replaced the 38-gauge copper wires in those areas (total 6 wires) with thicker wires (34 gauge) to provide more support on areas close to the three components. During weaving, we introduced a few more serpentine wires and coils between the MCU PCB and the energy harvester and the IMU3 to provide additional support during hand movement and bending.

To account for the more unpredictable environment in the field study, we implemented additional error detection and correction mechanisms in firmware. An IMU could be reset up to 2 times (2 read cycles) consecutively when the amount of retrieved data was abnormal — first the IMU itself and then the I2C bus the IMU was on. If the IMU still did not recover, the MCU would turn it off to conserve power for the rest of the study. In addition, we implemented a watchdog timer that would automatically reset the MCU if it was not responding, which could be caused by errors while reading from the IMUs or writing to the SD card. To assist with debugging and recovering data that might be corrupted, we created an error log text file in the SD card that would document each firmware or manual reset along with its timestamp. The LED indicator on the MCU PCB would also blink twice in case of an error.

4.4.2 Probe Deployment for the Field Study.

Participants. We recruited 7 external participants: three females and four males, ages 20-31 (M=26). Participants were compensated with a 25 USD gift card.

Procedure. The study consists of (1) a pre-survey (10 min), (2) the wearability study phase (6 hours), and (3) the post-study interview (30 min). A pre-survey collecting demographic data and participant hand-measurements was administered prior to the study. Similar to the preliminary study, the data gathered from the hand-measurement survey enabled the researchers to fabricate a custom-sized WovenProbe for each participant.

In the wearability study phase for the in-the-wild user study, all instructions and interviews were done remotely to mitigate risk during the COVID-19 pandemic per IRB protocol. Before the study, a WovenProbe along with skin adhesion materials was delivered to the participants' houses. A Zoom call was performed at the scheduled time to begin the study. After the consent process, participants were introduced to the study procedures. Next, participants were given both visual and written instructions on the device attachment and removal process. Participants wore the WovenProbe on their non-dominant hand using the same method that we used during our pilot testing. To determine the functionality of the device, participants were asked to perform five different gestures including hand waving, hand flipping, demonstrating SOS Morse code by slapping on the table, tapping index finger on the table (with palm placed on a table), and tapping thumb on the table. Each gesture was performed five times. Throughout the study, we followed the same protocol used for the pilot testing. Participants wore the device for

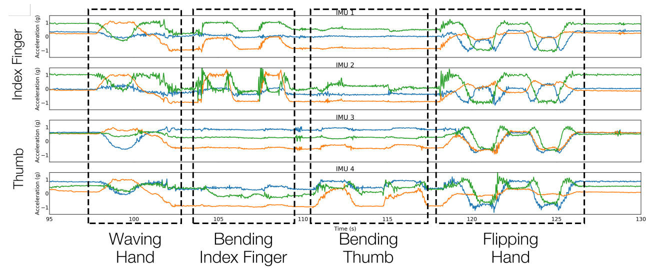

Figure 5: IMU traces for different gestures.

a total of six hours while performing their daily activities. Participants were encouraged to use hand sanitizer or wear disposable gloves provided by the researchers in lieu of water contact for hand washing. Hourly in-study questionnaires and photos shared by the participants were used to evaluate the mechanical durability and electrical continuity of the device.

A post-study interview, along with a post-study survey, was administered to gather participant perceptions towards the device. During the semi-structured interview, participants were asked to rate their subjective experiences while wearing the device and were allowed to discuss their opinions and observations, providing deeper insights into how the design and experimental factors contributed to the user experience. A Likert Scale (1=most negative, 7=most positive) post-study survey was used to evaluate the comfort and social perception of wearing the device in an everyday setting. Upon completion of the post-study interview and survey, participants removed the WovenProbe from their non-dominant hand with a sprayed layer of Pros-Aide remover. Finally, participants were asked to provide their feedback on the device removal process.

Analysis. Audio recordings of the semi-structured interviews were manually transcribed to identify salient themes. All qualitative data in the post-study interview underwent iterative coding by three experienced researchers. Then, all of the authors discussed the meaning of the text to identify common themes. We used codes with a reasonable degree of agreement to identify salient themes based on thematic analysis [75].

The IMU data stored in the SD card was analyzed using Python script and the Matplotlib library.

4.4.3 Field Study Results.

Technical Assessment of WovenProbe. The IMU data for different gestures are demonstrated in Figure 5. During the field study, the WovenProbe maintained adhesion to the skin over the course of 6 hours for all participants (Figure 6a–P1-P7), resulting in 13.9 million data points (26.5MB) on average per person. Similar to the pilot study results, slight detachments were noticed towards the fingertips, wrist and the areas adjacent to the electronic components. The IMU components had detached at the fingertips for P2, P3, & P6 and so had the edges on the wrist area for P4 & P7.

The device was fully functional over the course of 6 hours for all the participants except for P3 & P4 and no electrical issues were observed (Figure 6b—P1-P2, & P5-P7). For P3, the MCU was working for the entire duration except for one manual reset at 2 hours and

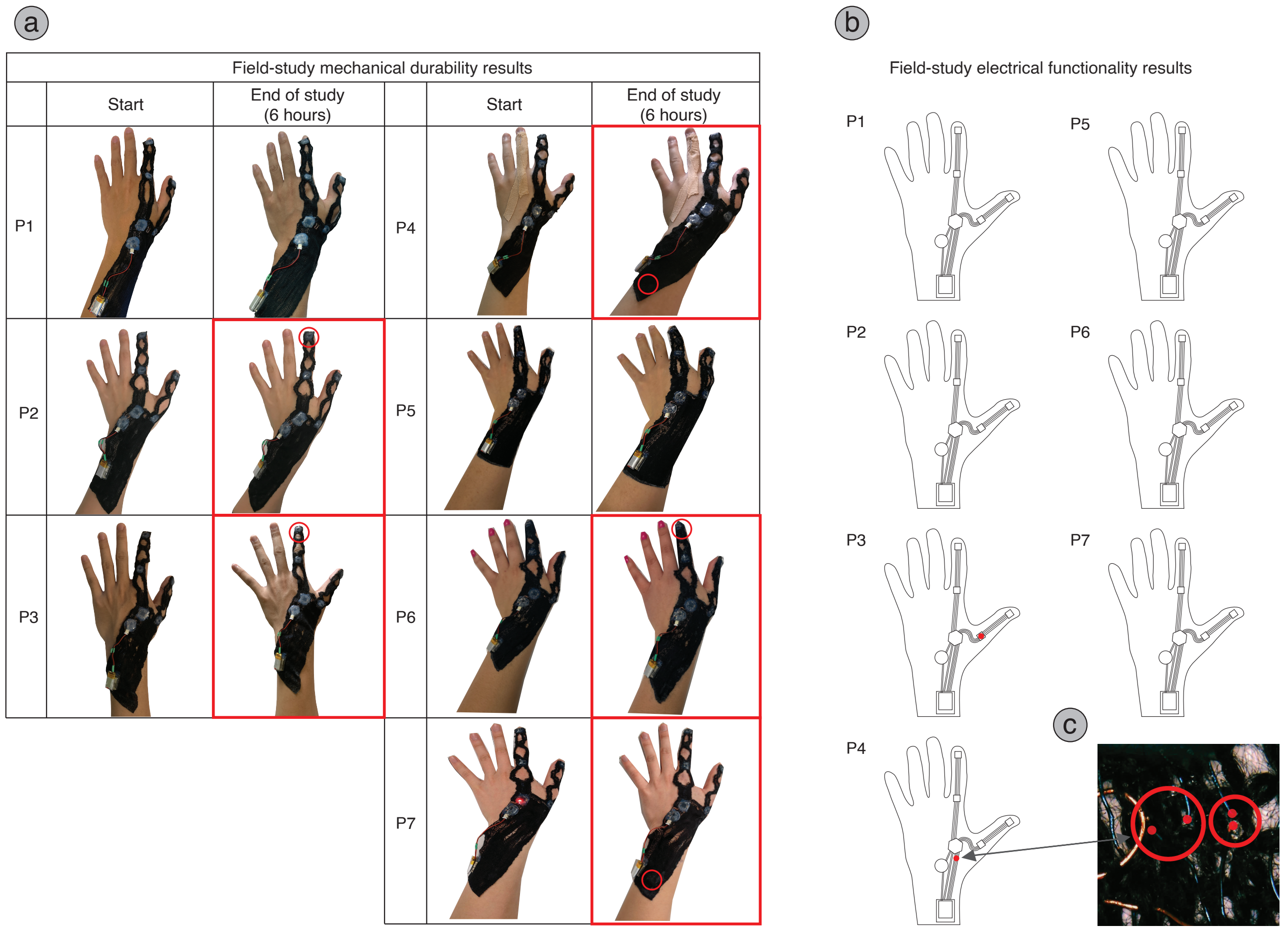

Figure 6: (a) Mechanical Durability Results: The device adhered to the participant's non-dominant hand from the 0th hour (first column) to the end of the 6th hour (full study, second column). Components had detached in small areas from a total of five participants' hands, with the red circles marking the area of detachment. (b) Electrical Functionality Results: Red indicates wires that had broken and lost electrical continuity on each participant. The red dot indicates the approximate location of the failure. (c) Close up of wire breakage for P4 (blue wires).

50 minutes into the study after the LED indicator showed an error (Figure 6b-P3). After the manual reset, the MCU worked until the end. While analyzing the data, we have observed some errors in IMU3 & IMU4 after the reset. Though we didn't notice any wire breakage within the system, we suspected that the connections near IMU3 might become weak and unstable, causing the glitches in readings. For P4, the device worked for close to the entire study duration (5.4 out of 6 hours) with the exception of two manual resets. We attributed this to breakages at the SPI signal wires (VDD and MOSI) between the main PCB and SD card (Figure 6b-P4, closeup of wire breakage at Figure 6c). For both P3 and P4, we observed that wire failures happened at locations close to the connection to PCBs.

Social Assessment of WovenProbe. For the social assessment of the WovenProbe, participant responses range from how comfortable and desirable they personally felt while wearing the device, to being accustomed to the device, to how they felt themselves being viewed by others. Participants rated both the comfort of the device and becoming accustomed to the device positively with a median (M) of 5 and 5.5 respectively out of 7 in the post-study questionnaire. In the post-study interview, P1 mentioned that he forgot it was there and "didn't really pay attention to the device," except for the occasions where he had to "grab something from the backpack." P2 mentioned that the device was "very comfortable" and she was not fully aware of the device either. P3 felt wearing the device was "normal". We received similar responses from the rest of the participants. P5 felt the device at the beginning "when there is some movements in the hand"; P6 felt "fine" wearing the device though she was "a little cautious at the beginning" and thought she might break it though that changed overtime; and finally, P7 felt "I forgot about the device until I looked into it." However, almost all of the participants agreed that they got used to the device after some time (M=5) and that it was minimally invasive to their daily activities.

Participants reacted positively (M=6) regarding device adhesion. Participants mentioned that most of the time the device stayed on their hands except in the fingertip areas where it was slightly detached, in particular when they tried to engage in activities that involved a great range of hand and finger movements, i.e., grabbing or lifting items (P1, P6), typing (P2, P3, P5, P6), playing piano (P3, P4), making tea (P6), driving (P6), folding and cutting paper (P7), using measurement tape (P7), plugging and unplugging plugs and sockets (P7), and donning and doffing (P4, P6, P7).

Our participants were mostly neutral in their perceptions of the ease of attaching the device on the skin (M=4). For instance, P5 found that "it's easy to apply on the skin"; P7 thought that it would be "a little difficult to wear it but overall it's not that difficult"; and P3 found that the device attachment process a bit time-consuming (10 minutes), mainly due to their unfamiliarity and the use of a smaller brush size for applying the lash glue on the skin. When asked about how comfortable it was to remove the device from the hand, most of them reported the process was comparable to removing normal glue (P1, P4), and Pros-Aide remover made it easier to remove the glue from hand (P5); though in some cases, glue stayed on hand after the device was removed (P2, P3, P6).

Participants were also asked to explain their experience of wearing the device in public: how it made them feel and how they felt about the appearance of the device. They were also asked to express any comments they had about other people's reactions to the device. Participants reacted positively regarding wearing the device in public (M=5). Participants reported that the device invited questions from on-lookers in public spaces, most of which were curiosity oriented. For instance, P4 had an doctor's appointment and the doctor was intrigued by the novelty and uniqueness of the device and asked him questions about the device and its functionality. A classmate of P7 thought the device was "very cool" and showed curiosity toward the device and its functions. In general, participants felt comfortable about the device being seen by other people and that the device wasn't disruptive to their day to day tasks and easily adapted to their daily routines.

Design Assessment of WovenProbe. During the post-study interview, all participants mentioned that the device fitted well to their hands. When compared with wearing traditional wearable form factors such as smartwatches, participants mentioned that the device was low profile and soft. All seven participants mentioned that they had never worn anything like it before. P6 mentioned that "WovenProbe was more durable than smartwatches since it's secured to my hand." Participants were positive about the aesthetic of the device (M=5). In the post-study interview, most of the participants were interested in wearing the device occasionally, if not regularly (P4, P6, P7). Many participants expressed interest in aesthetically customizing the device, especially to reflect one's personal style. Participants mentioned that they would be willing to wear this device more frequently if the device came in different colors other than black (P4, P5, P6), was more skin-like or had transparent color (P2), covered the whole hand instead of just two fingers (P3), covered just the fingers instead of the hand (P6), or came with more realistic functionality (P7).

Broadly, WovenProbe received positive feedback from all of the participants for its "lightweight, flexible, and ergonomic form factor" (P1, P2, P5, P6) and its ability to easily blend with daily activities (P4, P6, P7). Participants were quite impressed with the "novel and futuristic" (P1, P3, P6) features of the device. We also observed that the functionality and aesthetics of the device were key drivers for their subjective preferences. Participants envisioned several uses including tracking vital signals (P2, P6), tracking hand movements while playing sports (P5), helping surgeons while performing operation (P4, P7), detecting finger injuries and providing post-injury therapy (P4), navigation tool for blinds (P7), and using it as an alternative to displays (P1). We also received some device-specific feedback on improving the interaction experience, including finding an alternative to glue for the attachment process (P7), using a cover to hide the exposed electronics (P5), and replacing the silicone with a clear and more flexible insulation material (P1).

4.4.4 Discussions.

- **Connectors.** The PCBs for the field study were designed with castellated holes, onto which wires were soldered, for miniaturizing the surface area. The castellated holes facilitate soldering by ensuring that the wires are immersed in adequate solder. The alignment of wires to the circular notches also guarantees a uniform spacing between adjacent wires. However, while castellated holes occupy smaller area compared to through-holes, we found their mechanical strength to be weaker. The conductive plating tends to detach after repeated soldering, especially for thin PCBs. In addition, at the boundary of the solder joints, where the wires transition from being rigid to flexible, wire breakage might occur due to fatigue, i.e., the repeated stress as the PCBs bend or slide relative to the fabric. It could be worthwhile to explore solder pads on the bottom of the PCBs for connections, as the edge of the boards will no longer be constrained by wires. However, such an approach might complicate the removal process of the boards due to the close proximity of the solder and fabric. Alternatively, a flexible substrate could be adopted between the PCBs and the fabric, so that the flexible substrate acts as a stress-relieving buffer between sections of wire on PCB and embedded in textile [53].
- **Sizing and Adhesion to Skin.** Due to the fingers' multiple joints, it was vital for the stretchable lace weaves to be well aligned with the knuckles. However, we faced two main limitations due to COVID-19 study restrictions: (1) We could not physically see and measure the participant's hand, and instead could only rely on participant-inputted pre-survey data. The participants were inconsistent with what they considered to be the bottom and top of their finger and thumb joints, so some data seemed to misrepresent their hands' proportions. While the researchers who wove the devices could intuitively interpret the data for a fit, a more precise measurement would benefit the process. (2) We could only provide remote support for applying the interface to the participants. In some cases, participants tended to attach the energy harvester and MCU PCB closer to the wrist (a high-flexion region) instead of the back of the hand, which has a more planar surface. In the future, it could be helpful to designate a few starting alignment points to support precise placement (e.g., specific alignment points at the top of fingers or the web of the hand).

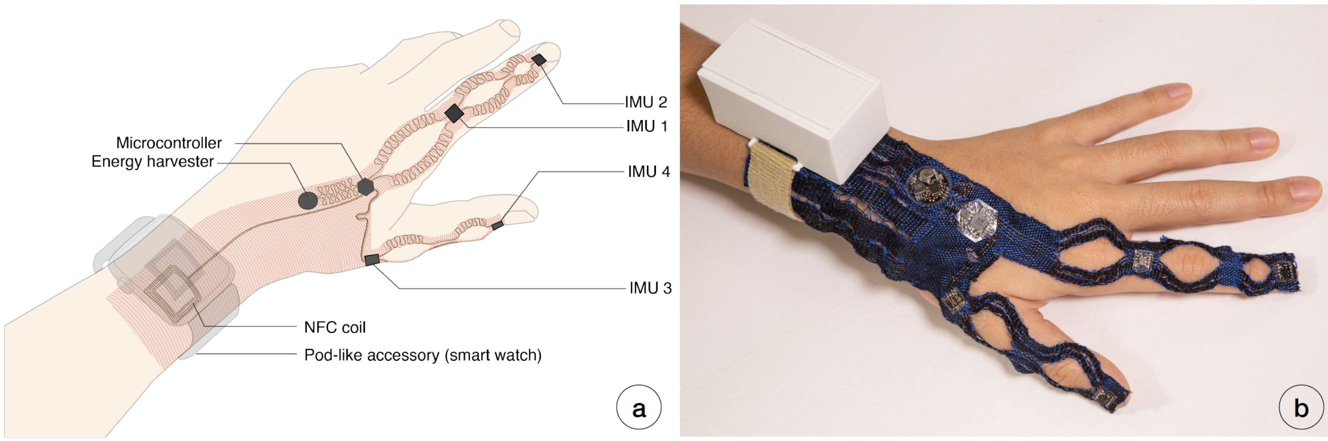

Figure 7: (a) Case study of an extended WovenProbe with wireless powering capability. The difference with the original one is the integrated NFC coil at the end. This coil is able to harvest energy from a pod-like accessory (smartwatch), and to transfer the sensing data back. (b) Implementation of the system.

4.5 Case Study: Wirelessly Powered IMU Hand Sensing System

While batteries were used for powering our user study prototypes, they pose certain physical limitations for on-skin interfaces due to their bulky form factor and finite lifetime. They also need to be recharged regularly which can be a burden for users of on-skin interfaces. One potential solution is to delegate the battery to a different accessory, for example, a smartwatch, which wirelessly charges WovenProbe. In this case study, we demonstrate the feasibility of extending our weaving technique to integrate a charging coil to harvest energy and offload the data, shown in Figure 7. Our supplementary video provides a demonstration of several performed hand gestures along with the data collected through NFC and stored in the SD card plotted.

4.5.1 Energy Harvesting and Data Transfer. Near-field communication (NFC) is a wireless technology that transfers power between integrated components via inductive coupling between coils, where the transmitter generates an oscillating magnetic field and the receiver picks up the field to retrieve power. NFC-enabled devices can be battery-free, economic, and have the ability to work over a short range, making them particularly suitable for on-body interfaces [14, 48, 49, 69, 71]. However, traditional NFC devices are usually made of rigid or semi-rigid materials such as silicone [36]. While recent on-skin works have fabricated slim NFC coils [39], they remain standalone components and are challenging to integrate with other circuitry due to lack of sturdy substrates, limiting their ability to be incorporated with thin on-skin systems. Using weaving's unique structural qualities, we can seamlessly integrate NFC coils into a substrate itself as part of an on-skin system, enhancing the overall flexibility and robustness of the wireless system. When combined with energy harvesters, NFC powered systems can also capture data when the tag is not powered [5, 12, 46], as demonstrated by our prototype.

Figure 8a illustrates how we take advantage of NFC and offload the battery and data storage to a separate NFC-enabled accessory (e.g., a smartwatch substitute in our example). In our system, the smartwatch serves as a NFC reader, and the WovenProbe is a NFC tag. We integrate a NFC coil, using either tapestry weaving or double weaving technique for enabling RFID charging capabilities of the device (described in detail in Figure 2-b3.1, b3.2 & closeup d3). We implemented the NFC communication using the AS3953A chip (Figure 4b). This specific chip supports high communication speed (up to 848kbits/s) and can deliver up to 5mA at a user programmable voltage level. The energy produced by the AS3953A chip is harvested by a TI BQ25570 harvesting chip with an 80mF supercapacitor as storage. The BQ25570 was selected because it relies on an efficient buck converter to convert the energy stored in the supercapacitor (max 3.3V) to the system 1.8V rail. To reduce the energy draw on the smartwatch, it was very important to reduce as much as possible the amount of time the reader was on either to transfer data or transfer energy. To reduce the overall power consumption of WovenProbe, we ran the MCU at 4.2MHz during data handling and put the MCU to Stop mode when idle. To keep the data transmission time to a minimum, we made extensive use of the direct memory access (DMA) feature. This allowed WovenProbe to read IMU data while sustaining 424kbits/s NFC transfers.

4.5.2 Smart Watch Substitute. We discovered that very few watches embed NFC reader hardware. The only watch we found equipped with NFC reader (Sony SmartWatch3 SWR50) did not provide a reliable API documentation. Out of concerns about the feasibility of this approach, we designed our own data pod to interface with the WovenProbe. The pod is built combining an Adafruit ItsyBitsy M4 Express board with an RFID Click NFC reader and an SD card to store the gathered data. The three components are housed in a 3D printed box together with a 3.7V, 290mAh LiPo battery, which is typical for a smartwatch.

4.5.3 Results. To evaluate the overall performance of our system, we used our smartwatch substitute with the casing to record the data captured by our WovenProbe prototype resting on a bench. The test ran for 10 minutes during which the WovenProbe's 4

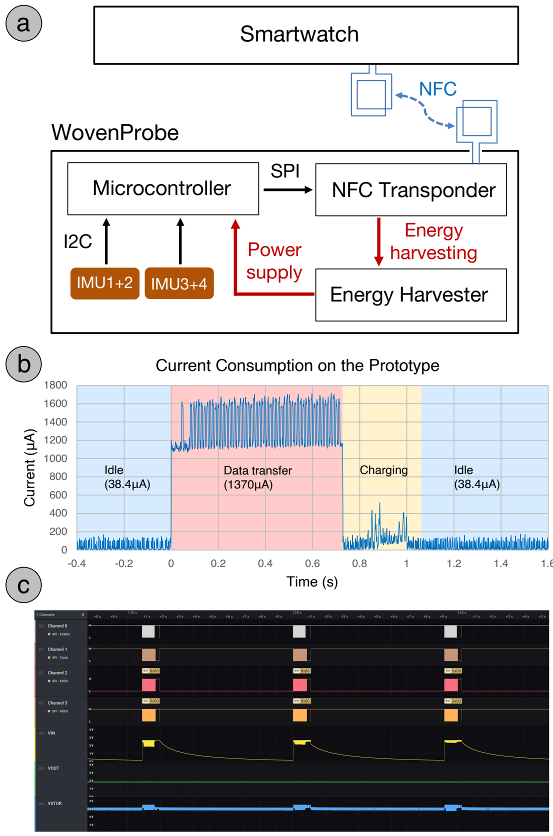

Figure 8: (a) NFC energy harvester operating diagram. (b) Current consumption measured on the NFC prototype for the 2 seconds around data transfer. (c) Typical transmission cycles showing the SPI bus activity for the reader module, as well as voltages on the energy harvesting system. With the reader inside its casing, the system duty cycle is 11.56%.

IMUs captured accelerometer data at 52Hz. During the test, the smartwatch substitute was reading the data every 9.15s. It took about 762ms to transfer the data (1370μA on average, 1720μA peak) but the field was left on for a total of 1060ms to provide enough energy to power the WovenProbe during the off phase (38.4μA on average) (Figure 8b). This corresponds to a 11.56% duty cycle (Figure 8c). The current spikes observed during the idle phase are created by individual IMU measurements at 52Hz. The spikes during the data transfer are caused by the MCU reading data packets from the IMUs through I2C and transmitting them through NFC. It is important to note that the MCU and data buses are using a significant portion of the energy harvested during the actual transfer. In practice this means that the performance of the system will improve as the sampling frequency goes down. With respect to the watch power consumption, our very simple implementation consumes 28.39mA at idle time, but 60.10mA while the field is on.

We tested the firmware on a worn prototype and got reliable IMU data collection for 10 minutes with the same 11.56% duty cycle (Figure 7b).

5 DISCUSSION, LIMITATIONS, AND FUTURE WORK

5.1 Challenges of and Opportunities for Longer Term Field Deployment

5.1.1 Manual Fabrication Effort and Opportunity for Mass Manufacture. Each WovenProbe device was custom fabricated for each wearer's hand. The major steps involved weaving the WovenProbe (7 hours), reflowing components onto PCBs (2 hours), soldering PCBs onto WovenProbe (2 hours), and finally insulating components using silicone (20 min). In total, it took around 11 hours and 20 minutes to fabricate a new device manually from scratch. Though it seems to take a lot of human effort due to the complex weaving techniques, miniaturized PCBs, and the extremely thin wires, most of these steps can be automated. While the hand-operated Baby Wolf floor loom successfully demonstrates the feasibility of our approach, the use of digital Jacquard looms can significantly improve the scalability and speed of the process. Further, by leveraging automated stenciling and pick-and-place operations, components can be efficiently integrated into woven structure. We envision that in the near future a personalized WovenProbe device can be created in mere minutes.

5.1.2 Front-end Software Design & Simulation Tool. On-skin systems must conform well to the wearer's body for longer term wear. Effective mapping of weave techniques (e.g., serpentine lace weaves) and wire sizes (e.g., slightly thicker 34 gauge wire) to specific body locations (knuckles and the connection between the MCU and the energy harvester, respectively) increases conformability. This process would be made more extensive by using a body scan and computer-aided design tool to model on-body design of the device, which would then automatically generate a suitable weave pattern and wire size mapping for appropriate body locations.

5.1.3 Waterproof and Insulation. An important move towards a deployable system is making the system waterproof. While the WovenProbe's PCBs and their connections are fully water insulated via silicone in the fabrication process, a water-proof test was not the focus of our study. However, to explore the feasibility of our insulation approach, we had one participant (P3) submerge his hand in water while wearing the device with the MCU working (LED blinking), except for the SD card and battery (Figure 9a). The MCU continued to work underwater with stable readings after a 4-minute test. We also tested the device under running tap water for two minutes, which had no effect as well. While our outcome is consistent with previous study results [55, 72], a more comprehensive study with multiple samples for an extended period of time needs to be performed to confirm the effectiveness of the insulation method. However, waterproofing with a sealant would make the prototype very hard to repair or replace, though it is a fair trade-off from a user point of view.

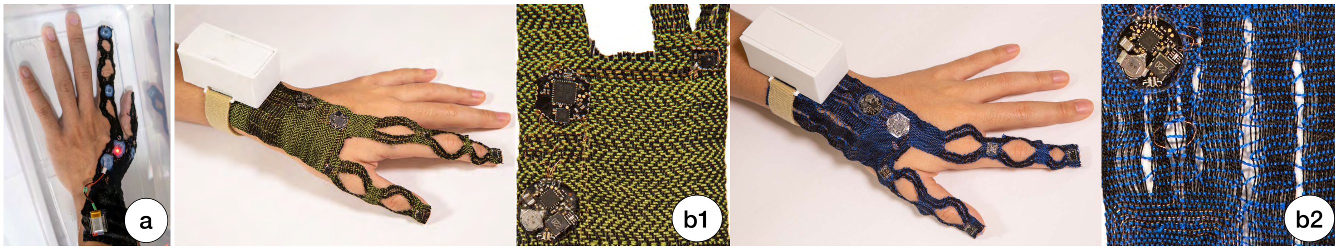

Figure 9: (a) Waterproof test. (b) Aesthetic customization of WovenProbe devices with unique weave patterns: (b1) Herringbone twill pattern and (b2) Spanish lace.

5.1.4 Aesthetic Customization Opportunities. Participants expressed interest in aesthetically customizing the device. During our post-study interview, many of them mentioned that they would be interested in wearing the device in everyday life, given that they have the opportunity to select from a range of styles and colors. Our weaving fabrication method not only supports complex structural and circuit functionality, but also offeres a wealth of aesthetic customization opportunities, built upon millennia of woven practices. Beyond graphic designs available in film-based on-skin interface fabrication techniques, weaving lends itself rich patterns and textures, as well as designs with lacing and unusual materials. We showcase the aesthetic customization opportunities of WovenProbe through 2 designs: a Herringbone twill pattern and a Spanish lace design. Herringbone twill (Figure 9b1), recognizable through its distinctive zig-zag pattern, is a popular pattern for suits and jackets. Through this design, we recall sharp, modern tailoring in an on-skin form. Spanish lace (Figure 9b2) is a hand-manipulated technique that we used to create a slimmer, more flexible structure for the joints, but we now capitalize on its aesthetic potential, extending its usage to all non-component locations to create a dainty design that reveals the skin underneath. By providing a wide range of aesthetic options to fit the wearer's personal preferences, wearers will be able to utilize this intimate form as a vehicle for personal expression.

5.1.5 Power Management. The NFC WovenProbe prototype achieves a 11.56% duty cycle, but it might be possible to reach an even smaller duty cycle by leveraging the embedded Machine Learning Core [2] in each IMU to process the captured data on the WovenProbe and limit the amount of data being transmitted through the RFID link. While, in this paper, we specifically investigate the application of NFC technology for wirelessly powering on-skin systems, in the future, other approaches for battery-free communication and energy harvesting such as ambient backscatter technology [8] could be realized to enable better performance for on-skin systems.

6 CONCLUSION

In this work, we introduce our research through design investigations in using an extended woven practice for developing WovenProbe, a multi-sensor and fully-integrated on skin system. Our fabrication approach blends the benefits of on-skin interface and textile fabrication techniques (e.g., weaving) to achieve a slim form factor and sturdy structure while maintaining the required electrical performance for an extended period. By combining complex woven structures and on-skin interface fabrication, we develop fully-integrated, versatile, and durable structural and circuitry topographies, which are difficult to achieve using existing film-based fabrication approaches. We designed, implemented, and deployed an untethered and fully-functional index-finger and thumb-based IMU tracking system as a *technology probe* to investigate the social, technical, and design challenges of designing on-skin systems for field deployments. The technology probe was deployed in a real setting for a multi-hour period in the workday with no major technical issues — the first study in HCI and wearable computing to do this, to the best of our knowledge, which shows the feasibility of using the technique for developing on-skin interfaces for use in real contexts. Furthermore, WovenProbe received positive reactions from the participants towards its versatile and seamless form factor. As an example case study, we further integrate an NFC coil into our WovenProbe and offload power and data to a pod-like accessory (e.g., a smartwatch) through RFID, signifying the potential of our woven approach for developing wirelessly powered fully-integrated on-skin systems for potential longer-term continuous wear. While we demonstrate our approach in the challenging case of hand-tracking systems, we believe it is equally extensible to a wide range of HCI applications which require direct skin contact to access a user's information. We believe this approach serves as a gateway towards realizing complex and deployable body surface interfaces.

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