Delocalizing Strain in Interconnected Joints of On-Skin Interfaces

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ABSTRACT

Durable and reliable fabrication of on-skin systems remains an open research question to enable developing on-skin interfaces at scale. One of the main challenges is the complexity in achieving robust devices to connect hard goods (printed circuit boards and electronics) with extremely soft materials (slim on-skin interface traces). This paper presents a systematic study evaluating the durability of 5 interconnection designs (including PCB shape, solder pad positions, and rigid versus flexible PCB) for on-skin systems under stretching and bending tests. The study results show the significant robustness of interconnects on flexible PCBs over rigid PCBs under bending and the better performance of elongated shaped flexible PCBs over shorter flexible PCBs. Further, we demonstrate that an interposer design consisting of 2 layers of flexible PCBs combines the benefits of both the rigid and flexible boards. Based on our experimental results, we present a set of design guidelines for PCB interconnect design for resilient on-skin systems.

CCS CONCEPTS

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

KEYWORDS

On-Skin Interface; Interconnects

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1 INTRODUCTION

On-skin interfaces, often in the form of smart tattoos or bandages, are a form of wearable computing that directly contacts the skin to detect physiological signals. It is regarded as one of the most effective platforms of any electronics-embedded system for assessing a person's activities and needs [1]. However, while significant efforts have been devoted to the development of on-skin interfaces in the past decade, many obstacles still impede scalable and robust fabrication [31]. One of the key bottlenecks is the transition area, i.e., *interconnection joints* between the hard material (PCB) and the soft substrate (on-skin circuitry), which is typically subjected to the highest stress and has the smallest bending radius and hence, more prone to breakage [7, 10, 17]. While one could argue for on-skin circuitry without integrated PCBs, these would severely limit the sensor complexity of the devices.

By improving the durability of the mechanical and electrical interconnections between hard electronics and soft on-skin circuitry, we aim to enable seamless integration of electronics into slim on-skin interfaces imperceptible to the wearer and durable enough to survive in extended wear tests.

In this work, we utilized an existing fabrication technique [7] of integrating flexible PCBs (FPCB) into a woven on-skin system where conductive traces are directly woven into a slim fabric substrate and prefabricated surface-mount components are populated using a soldering technique (Figure 1). By testing different designs of the woven on-skin system, we aim to isolate and identify ways to relieve the interconnect joint stress to allow for flex and motion and to prevent extreme bending. Here, we evaluate in-depth the geometry and mechanical properties of the interconnection joints between the PCB and the integrated traces while adding additional support materials within the system. We explore different materials, PCB components and pad shapes and sizes, techniques for handling and mounting the components, and component and circuit design features to maximize the durability, reliability, and scalability of the system. Finally, the failure mechanisms under different circuit parameters are investigated with tensile and bending tests. We conclude with design guidelines on PCB interconnects for resilient on-skin systems for the research community.

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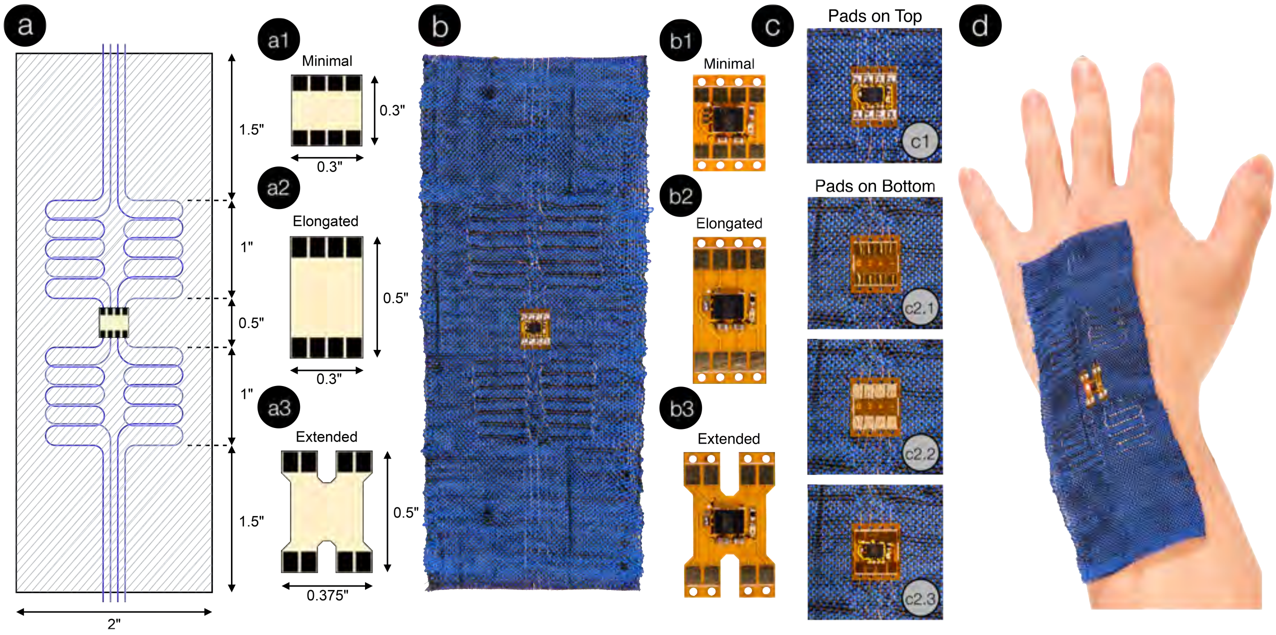

Figure 1: (a) Schematics of the woven samples with integrated serpentine copper wires for bending tests. Three PCB shapes were investigated: (a1) Minimal, (a2) Elongated, (a3) Extended. (b) Example of a woven sample along with the reflow soldered flexible PCBs (b1-b3). (c) Soldering processes for FPCBs with pads on the top surface (c1) and bottom surface (c2.1-c2.3). (d) A prototype worn on hand.

2 BACKGROUND AND RELATED WORK

2.1 On-Skin Form Factor Fabrication Processes

Several attempts have developed on-skin interfaces in soft, stretchable forms that can adhere seamlessly to the skin [6, 9–12, 18, 20, 22, 27–30]. Previous research has explored *film-based approaches*, which are derived from flexible electronics manufacturing methods with thin silicone or conductive films layered on top of each other [8, 11, 18, 28, 29]. An emerging alternative approach that takes advantage of *yarn-level structures* [7, 24], more often produced in constructed textiles [21, 23], can easily conform to body contours. In particular, weaving presents a rich platform for versatile circuit topographies and affords scalable manufacturing, providing unique benefits over film-based approaches. Besides, comparing to other fabrication methods such as knitting or sewing, weaving's unique structure where two sets of yarns intersect with each other perpendicularly offers easy incorporation of delicate electronic components and thin materials as well as diverse trace routing. These features make weaving particularly suitable for on-skin interface fabrications [7], which we adopt for the on-skin substrate in this work.

2.2 Durability of On-Skin Interface Systems

To date, the primary focus has been developing novel fabrication processes and applications for on-skin systems, with less emphasis on developing fully integrated systems where all the necessary hardware components including central processor, power source, and data storage are seamlessly integrated. Oftentimes, they are external rigid units connected as add-ons to the on-skin device [11]. A few projects have attempted to fully integrate spatially distributed PCBs into on-skin interfaces [7, 10]. These works report that the areas most prone to breakage are the interconnect joints between the rigid PCBs and the soft on-skin traces [7, 10]. However, to date, no research has centered on characterizing and improving the design of interconnects for improved durability of on-skin systems, which this work aims to contribute.

2.3 Interconnection Methods for Soft Circuitry

An "interconnect" can refer to different things in electronics: (1) The connection between two electrical terminals, or (2) the actual "joint" making a mechanical and electrical bond to interlock components in electronics [2]. For clarity, in this project, we refer to the latter meaning in regard to the actual joint making the connection.

Integration of hard goods into soft interfaces has been examined in the form of *garment-integrated* and *on-skin interface* systems: **Garment-integration** incorporates PCBs directly into fabric via stitching [15], sewing [25], soldering [14], thermoplastic adhesives [26], and non-conductive adhesive under pressure [16]. In addition to the integration of PCBs, a few attempts have been made to attach discrete component packages into textiles [13, 21].

Studies have identified that the transition area between the rigid electronics (PCBs) and the textile is typically subjected to higher stress [2, 21]. To improve the stability and strength of interconnecting joints, stabilizers have been used to provide additional support for flex and motion and to prevent extreme bending for wearables [5]. In addition, previous research explored stabilizers as an interposer to allow complex circuit routing [19]. A few studies attempted to manipulate the geometry and material of the traces to accommodate high mechanical stresses and additional flexibility such as horseshoe-shaped traces [4] and embedded traces in silicone [3].

On-Skin Interfaces. Effective connections between slim on-skin interface traces and the rigid PCB hardware in Wearable Computing and HCI remain unresolved. While the current connection points remain undiscussed, typically, they are implemented with makeshift temporary wires or attached via Z-tape [28] or conductive fabric tape [11] to the on-skin circuitry. For instance, in DuoSkin [11], the tattoo-like on-skin circuitry is connected to the external hardware via rigid wires and conductive fabric tape. Inexpensive yet robust methods for connections have rarely been discussed in current on-skin interface systems in Wearable Computing and HCI. Yet, these connection points are often the first areas of breakage for systems worn by end-users [7, 10]. This project especially aims to isolate and tackle this issue.

3 METHODS

In this paper, we explored different weaving techniques, pad shapes, sizes of PCBs, techniques for handling and mounting the PCB components onto the on-skin substrate, and circuit design features to maximize the durability of the interconnections (Figure 1).

3.1 Design Goals

Towards Mass-Producibility: We aim to demonstrate the potential of scalable manufacturing of on-skin systems by weaving conductors into an on-skin substrate using standard weaving machines and affix custom-made PCB components using standard and/or automatic machines (e.g., reflow soldering, hand soldering tools).
Seamless Integration of Technology: We use custom-fabricated flexible PCBs without large bulky areas to allow an even transition between the rigid electronics and the soft textiles, improving the overall conformability of the on-skin systems.
Durability and Long-Term Usability: By adjusting the size and shape of the PCBs, we redistribute and relieve the stress in larger areas of the interconnection joints between the flexible PCB and integrated woven conductive traces, which allows the connections to remain unharmed against high stresses on the body.

3.2 Material and Process Selection for Fabricating On-Skin Circuits

3.2.1 Weaving Conductive Traces. We extend weaving techniques explored in the related works [7, 24] to develop durable interconnections. For this work, we developed a woven on-skin substrate with embedded conductive materials. The substrate is made of non-conductive yarns (Nm 60/2 silk yarn), which has been identified as the most suitable choice among all yarn materials by previous works [7, 24]. For the conductive materials, we used 38 gauge copper wires. We adopted plain weave as the base structure and supplemental weave technique for embedding copper wires into the fabric. We used a serpentine pattern for the copper wires to allow more flexibility and stretchability as well as to improve the overall durability of the circuit (Figure 1-a,b).

3.2.2 Interconnections for PCBs. The main goal of designing the circuit layouts for PCBs was to distribute the interconnection joint stress in the surrounding areas within the on-skin system. We designed and fabricated circuit boards with three different layouts by adjusting the shapes and sizes of the PCBs: (1) Minimal (0.3×0.3 in.): a square-shaped board with minimum dimensions (Figure 1-a1, b1); (2) Elongated (0.3×0.5 in.): a board elongated along the traces, allowing more flexibility in the vertical direction (Figure 1-a2, b2); (3) Extended (0.375×0.5 in.): a board with 8 pads distributed to 4 legged structures, allowing additional flexibility in the horizontal direction (Figure 1-a3, b3). The groups of 4 pads on each end were connected to the I2C bus of an ST LSM6DSOX IMU as well as an LED power indicator. The size of each pad was 60×60 mil for the Minimal design and 60×80 mil for the other two. To offer more flexibility and to remain stable against extreme bending of the circuit, we utilize pre-fabricated flexible PCBs with 0.15mm thickness. For each of the three designs, FPCBs were manufactured with pads on the top surface. To evaluate the effects of pad locations on durability, we also built and tested PCBs with pads on the bottom surface for the Minimal design. In addition, we tested a rigid PCB with a layout and dimensions similar to the Minimal design as a comparison.

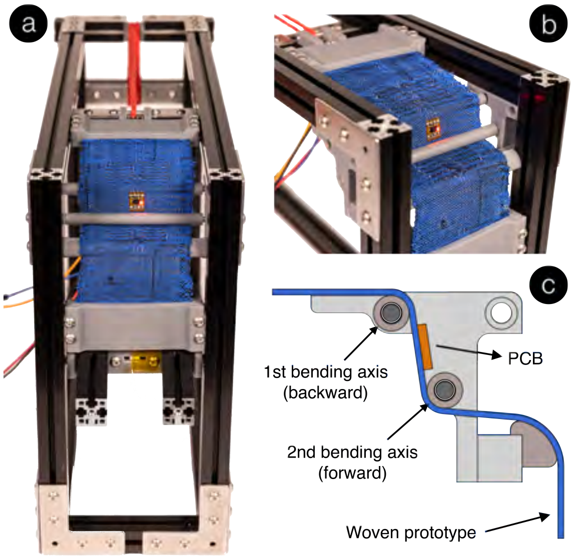

Figure 2: (a) Apparatus for the bending test. (b) Side view of the device. (c) Schematics showing the two bending axes and the woven prototype.

3.2.3 Integrating PCBs onto Woven On-Skin Substrate. To integrate the five PCB designs mentioned in the previous section onto the woven on-skin substrate, the enamel coating at the leads of the copper wires was removed using sandpaper. For the FPCBs, a non-conductive hole is reserved for each pad, allowing the copper wire to go through it before reaching the conductive pad (Figure 1-b1-b3). For boards with pads on top, the wires go through the holes from the bottom and were then soldered onto the pads using a soldering iron (Figure 1-c1), which protects the interconnections by restraining the movements of wires relative to the fabric. For the board with pads on the bottom, we used an additional layer of FPCB with only conductive pads on top as an interposer. The interposing FPCB was first adhered onto the fabric and wires were aligned with its pads using the holes as guidance (Figure 1-c2.1). Then, a layer of low-temperature solder paste (137°C melting point) was applied on top of the wires and pads using a stencil (Figure 1-c2.2). Lastly, the FPCB with components was placed on top and heated with a heat gun set to 150°C (Figure 1-c2.3). The low melting point allows the textile underneath to remain undamaged.

3.3 Testing Procedures

3.3.1 Tensile Test. The Minimal designs for both the rigid and flexible PCBs, which serve as baselines for other design variations, were tested using the Instron Universal Testing System (Instron 5566). Samples were mounted on the Instron with the sections of serpentine wires positioned between the two clamps. The samples were elongated at 0.5mm increments and held for 2 minutes. Throughout the test, the IMU readings from the PCB were monitored using an Arduino. After each extension, the maximum tensile force achieved was recorded and the interconnections were checked with a multimeter. The test was stopped after the elongation reached 15mm, or approximately 24% uniaxial strain in the warp direction.

3.3.2 Bending Test. Previous studies [7] suggest that interconnections located close to high-flexion regions, e.g., wrist, have the highest chance of breaking due to fatigue, i.e., the repeated stress as the fabric bends relative to the PCBs. Therefore, a bending test would be an effective method to evaluate the durability of various interconnection designs. We built a bending machine tailored to the dimensions of our woven on-skin interface samples (Figure 2a). Two bending axes with 6mm diameter bend the fabric from opposite sides at approximately 90° angle, simulating the movements of the wrist (Figure 2c). The sample was clamped to two sliders with the lower one pulling the fabric down with an 80-gram weight. The top slider was pulled horizontally with a string. For each back and forth cycle, the PCB slides through each bending axis two times (four bends in total). Each sample was tested for 1000 cycles (4000 bends). Similar to the tensile test, the IMU readings were constantly monitored using an Arduino. For the first 200 cycles, the eight interconnections were checked with a multimeter every 20 cycles and every 50 cycles from 200 to 1000 cycles.

4 RESULTS AND DISCUSSION

4.1 Effect of Interconnection Joints on the Durability of the Circuits

4.1.1 Rigid vs Flexible PCB. Both the rigid and flexible PCBs remained functional after the tensile test with a maximum 24% stretching before the fabric was torn apart. We observed that the serpentine pattern of copper wires distributed the strain and prevented the interconnects from being stretched drastically.

The interconnects on the rigid board sample were less durable to bending: all 8 interconnects broke after 228 times of bending (Figure 3-a). The FPCB samples (sample 2-4) showed better bending resistance (the first breakage happened after 1000 times of bending, and 4 out of 8 interconnects broke after 4000 times of bending), but internal trace breakages were observed, which indicates that the circuits were less durable.

4.1.2 Size and Shape of FPCB. Both Elongated and Extended FPCB samples performed slightly better than the Minimal design in the bending test due to the increased portion of the flexible area, considering the solder and the components are rigid. In this sense, we expect the Extended FPCB design to be more durable to horizontal bending as well.

4.1.3 Interposing 2-layer FPCB. The interposing 2-layer FPCB was more bending resistant than the rigid PCB and had fewer internal breakages than other FPCB designs. The increased stiffness of the 2-layer structure protected the internal traces from breaking. Besides, the copper wires were sandwiched between two FPCB layers, so the interconnects were secured from exposure. Nonetheless, the bending performance of this design is compromised compared to other FPCB samples due to the higher stiffness.

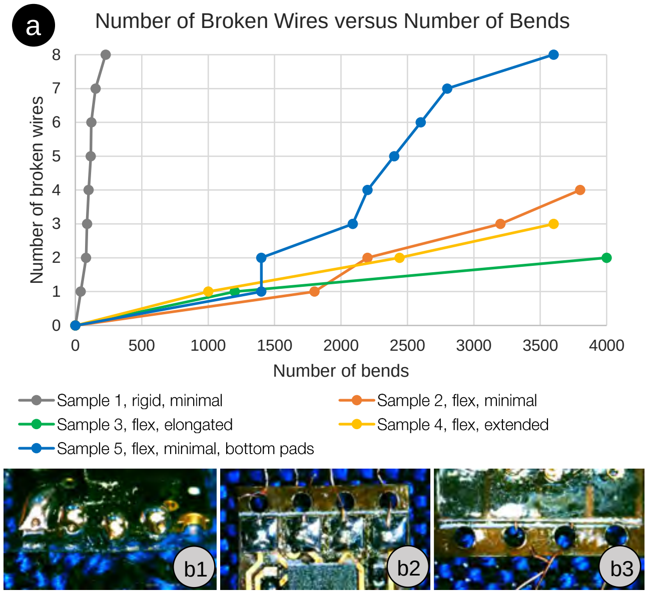

Figure 3: (a) Number of broken wires versus number of bends for the five tested samples. (b) Microscope images of the broken interconnects for sample 1 (b1), 2 (b2), and 5 (b3).

4.2 Causes of Failures

Figure 3b shows the magnified views of the broken wires after the bending test. All the wires connected to the rigid PCB broke at the surface of the solder joints, as this section is subjected to the highest stress when the on-skin circuitry bends against the rigid board (Figure 3-b1). Similar results were observed for the single- and two-layer flexible PCBs (Figure 3-b2, b3). All wires broke adjacent to the interconnects and near the edge of the FPCBs.

4.3 Opportunities of Mass Manufacturing and Automatic Testing

We aimed to isolate and identify ways to relieve the interconnect joint stress through the tests. Therefore, we controlled most of the variables such as fabric size, shape, warp spacing, serpentine pattern of the copper wires, etc. Ideally, the interconnect design should be the only independent variable. However, the manual fabrication of weaving, soldering, and the reflow process might introduce minor variables such as the quality of woven on-skin interface or amount of solder/soldering paste that can affect the durability performance. The averaging results from repeated tests of the same design might also help reduce random errors that were not handled in the current experiment settings. Thorough exploration can be achieved via mass production of more configurations of interconnect design, along with repeated, fully automatic testing procedures to allow different parameters such as durability to be examined.

4.4 PCB Design Recommendations for On-Skin System Interconnects

We provide the following recommendations of PCB design for different on-skin interface usages based on our experiment results:

Incorporate serpentine pattern for circuit wires weaved/knitted in fabric: We observe that for both the stretching and bending tests, the serpentine pattern helps delocalize strain in the joints that connect the soft and rigid parts of the circuit. Note that the additional length of serpentine wire might lead to parasitic resistance or capacitance, which is normally acceptable in small circuits for on-skin interface.

Choice of PCB structure and material: This should be determined by how complex the PCB circuit is and how often the device would be bent. One can choose the rigid PCB if the device would stay on a flat body surface (e.g., back of the hand); otherwise, one should choose FPCB for devices that demand durability against bending. Meanwhile, the more complex the circuit, the more likely internal breakages would happen in the finer structure. For applications that require mild bending and relatively complex circuit design, we recommend utilizing the interposing 2-layer FPCB technique for the interconnects.

5 CONCLUSION AND FUTURE WORK

In this work, we investigated 5 designs of interconnection joints for woven on-skin systems. Through the stretching and bending tests, we identified trade-offs among the 5 designs and analyzed the possible causes of circuit failures. The results identified possible design options with different durability performances. We envision a broader test of different design parameters of the interconnection, including the use of silicone encapsulation, integrated stiffeners on flexible PCBs, and alternative conductive trace and interposer materials, can be achieved with mass manufacturing and testing.

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