WovenCircuits: A 3-Step Fabrication Process for Weaving Electric Circuit Layouts in Everyday Artefacts

Ahmed Awad*
Queen's University
iStudio Lab
Kingston, Ontario, Canada
a.awad@queensu.ca

Salma Ibrahim*
Queen's University
iStudio Lab
Kingston, Ontario, Canada
salma.ibrahim@queensu.ca

Sara Nabil
Queen's University
iStudio Lab
Kingston, Ontario, Canada
sara.nabil@queensu.ca

Figure 1: We explore WovenCircuits, a fabrication process to design seamlessly-integrated circuit layouts using digital weaving (right). Adopting a Research through Design (RtD) approach, we contribute a 3-step process (top) and a series of interactive research products that extend the functional and aesthetic dimensions of woven e-textile designs (bottom): a) PowerPocket Jeans for wireless charging; b) Thermo-Placemat for warming food; c) GoGreen Backpack for embodied expression; d) VibroChair Cover for posture correction; e) SensingRug for activity recognition; and f) ThirstyCat Tapestry for tactile animation.

Abstract

Previous work explored techniques for creating woven e-textiles, emphasizing interactive input and output elements. However, the integration of electrical connections and circuitry remains underexplored. Using Research through Design (RtD), we present WovenCircuits, a design-led inquiry into combining traditional weaving methods with computational design on digital Jacquard looms to create woven circuit schematics. Through iterative design experiments, we developed a 3-step process and characterized three fabrication techniques to: 1) weave insulated electrodes, 2) integrate rigid components into fabric, and 3) create woven electrical connections. We further examined their electrical behaviour through key design factors and evaluated the effect of washability on resistance and dimensions. To demonstrate its potential, we designed and built six high-fidelity research products showcasing diverse applications in interactive everyday objects. Finally, we reflect on the design opportunities and limitations of WovenCircuits, contributing to the growing body of knowledge on woven e-textiles.

*Both authors contributed equally to this research.

DIS '25, Funchal, Portugal

ACM ISBN 979-8-4007-1485-6/25/07
https://doi.org/10.1145/3715336.3735696

CCS Concepts

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

Keywords

weaving; e-textile; circuits; fabrication; hybrid craft; research through design; everyday things

ACM Reference Format:
Ahmed Awad, Salma Ibrahim, and Sara Nabil. 2025. WovenCircuits: A 3-Step Fabrication Process for Weaving Electric Circuit Layouts in Everyday Artefacts. In *Designing Interactive Systems Conference (DIS '25), July 05–09, 2025, Funchal, Portugal.* ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3715336.3735696

1 Introduction

E-textiles can be created using conductive yarns, fibres, and fabrics with a variety of crafting methods, including knitting [2, 52, 56], embroidery [14, 48, 62, 86], spinning [35, 49], crocheting [26, 67], and weaving [73, 78]. This enables the seamless integration of interactivity into everyday garments and objects as envisioned in Interioraction [64] and Decoraction [63]. Prior work has explored weaving as a structural-level integration approach, implemented at the crafting stage as opposed to post-production surface-level methods, resulting in slimmer, sturdier, and more seamless integration [12, 13, 19, 23, 31, 46, 57, 73, 78, 80]. We adopt a Research through Design (RtD) [90] approach to explore weaving electric

Figure 2: Collage of woven pieces of fabric and annotations in the lab book with sketches and the roll of fabric woven during the experimentation and research-through design prototyping phase. We show failed attempts as well as samplers, quantitative experiments of characterization, and some early iterations of research products.

circuit layouts for integrating rigid electronic components within interactive everyday things (see Figure 1).

Compared to other crafting methods, the main advantage of weaving lies in how the yarn is manipulated to create fabric and how the design process can be streamlined through computational design and machine-assisted prototyping. Weaving operates by interlacing vertical threads (warp) with horizontal threads (weft), producing fabric as a matrix of intersections between warp and weft. By controlling the interlacement pattern at the pixel level using digital looms, weavers can create unique multi-layered woven structures, enhancing the design potential of woven e-textiles [13, 73, 84]. Subsequently, we were motivated to explore how integrated circuits can be created using various weaving structures to achieve different effects and functionality [13, 78]. Researchers have made significant strides in developing software tools to help design weaving patterns and drafts for woven e-textiles and sensors [16, 20]. However, comprehensive guides for digitally weaving e-textiles are notably scarce. This prompted us to conduct design research to develop a formalized fabrication process for designing complete woven circuit layouts that build on techniques from existing literature and traditional weaving methods for HCI researchers, makers, and practitioners of e-textile prototyping.

Woven e-textiles offer many opportunities and new affordances for interactive devices. However, there are two main constraints that limit the weaving of complex circuits. These limitations hinder the creation of deployable wearables and woven everyday things. First, component placement is restricted to either the vertical or horizontal axis. This can present a significant challenge when weaving complex circuit layouts, particularly those with intricate pathways required to ensure proper connectivity. Second, the weaving process involves interlacing the weft yarn at each step. In cases where circuits require two or more separate parallel vertical conductive pathways, sharing the same conductive weft will cause the pathways to be connected. Throughout this paper, we will often refer to these conductive pathways and connections as 'traces'.

Inlay weaving is the technique of introducing a supplementary weft (an additional bobbin of yarn that is distinct from the warp and weft) to create patterns or designs, on specific locations of the fabric, that stand out from the main weave structure (warp and weft) [74]. The programmable nature of inlay weaving on Jacquard looms, where individual warp threads can be controlled, can offer a partial solution to these constraints by selectively incorporating conductive thread wefts to form specific shapes and create conductive traces. This contrasts Dobby looms, where inlay weaving would be an entirely manual endeavour since the warp threads in these looms are controlled in groups [74]. Current methods for creating woven sensors using inlay weaving on digital Jacquard looms [14] result in single-layer woven electrodes, which may not be ideal for wearable applications. Industrial looms address inlay weaving in a sophisticated and automated fashion, but they are typically inaccessible to maker spaces and unsuited for small-scale e-textile prototyping. This highlights the need for exploring an approach to weaving circuits that can be tailored to specific applications. Multi-layered weaving approaches [13, 74, 78] when combined with inlay weaving through the use of a supplementary weft is a promising technique that we will demonstrate through this paper. In addition, there is a notable gap in research addressing the implementation of complete electronic systems that integrate all the necessary functional elements, including interactive components, microcontrollers, power sources, and electrical connections.

In this paper, we present WovenCircuits, a weaving approach that builds on existing techniques to streamline the creation of complex woven circuit schematics, through the following contributions:

(1) A 3-step process and three fabrication techniques for weaving electric circuit connections and layouts, referred to as WovenCircuits (T1: weaving insulated electrodes using double-layer Ghost Inlays; T2: integrating electronic components into single-sided pockets; and T3: weaving electric connections with conductive thread traces and wire tunnels).
(2) A characterization of the electrical behaviour and washability of WovenCircuits, along with the identification and evaluation of three key design factors (F1: trace size; F2: weaving structure; and F3: yarn ply).
(3) Validation of WovenCircuits through six fully interactive, high-fidelity research products. These deployable artefacts showcase the workflow of our 3-step process, as well as the flexibility of mixing and matching the three fabrication techniques of WovenCircuits.

2 Related Work

2.1 Weaving E-textiles in HCI

E-textiles, or electronic/smart textiles, incorporate interactivity through textile-based sensing, functional, or actuating elements. These elements can be integrated using traditional handcraft techniques, such as sewing [65], crocheting [67], and punch-needling [28, 39], or through machine-assisted methods like knitting [2, 52, 85], embroidery [9, 48, 59, 62], and weaving [79]. Research has shown that weaving can enable the integration of interactivity during the creation of the fabric itself [79], offering customizable benefits and aesthetic richness [46].

However, the design phase for weaving, particularly for complex structures [88], can be challenging and less intuitive. This difficulty partly arises from the gap between the design process and the resulting woven fabric, since a 2D weaving draft can be designed to produce a multi-layered woven structure [16]. Prior work [12] addresses this issue by offering a beginner-friendly introduction to paper weaving in a simple activity book format. Another approach to bridging this gap [10] involves employing multiple methods, such as diagrams and paper models, to create a more intuitive design process for multi-layer weaving [78]. Inspired by the community's interest in simplifying e-textile weaving, we introduce WovenCircuits, which includes a straightforward 3-step fabrication process and enables designers to implement fully interactive objects and high-fidelity projects through three main fabrication techniques that act as building blocks for woven circuit designs.

2.2 Digital Weaving

Weaving produces fabric by interlacing vertical (warp) with horizontal (weft) yarns [13]. Hand weaving [76] involves predominantly manual processes, offering extensive customizability and flexibility, but can be time-consuming and labour-intensive [76]. However, digital weaving [68] automates much of the process, providing various levels of computational flexibility. While industrial machines are more expensive and offer less customizability than hand weaving [16], some digital Jacquard looms (such as the TC2 [66, 83]) provide hybrid capabilities with digital control and manual real-time customization, making them ideal for e-textile prototyping.

Previous work [3, 16, 17, 20] introduced digital design software tools for weavers, which translate the abstract binary representation of digital weaving drafts into more intuitive formats. For instance, AdaCAD [16, 20] is an open-source weaving draft design tool developed by (and for) HCI research. It empowers designers to utilize various weaving methods and techniques through parametric design components. Building on recommendations of recent work [12, 20], our WovenCircuits fabrication techniques utilize the capabilities of a TC2 digital Jacquard loom and the AdaCAD design software to customize circuit designs.

2.3 Woven E-Textile Circuits

2.3.1 Electrical Connections. Planning connection traces, also known as circuit routing [22], aims to achieve stable and secure electrical connections between circuit components. Previous work [18, 40, 44] on woven connections follow two main approaches for routing. The most common approach involves designing a grid of connectors, with the horizontal connectors aligned to the weft and vertical ones aligned to the warp [54, 55, 91]. The aim of this is to: 1) enable a uniform distribution of components since the spaces are uniform across the area of implementation [32, 91]; and 2) utilize the weaving structure to ensure proper insulation between adjacent connectors [55]. The other approach implements connections as inlays, which allows the wire to be freely woven between two points with no constraints on direction [30, 31, 78]. Although the latter approach provides more flexibility in routing and placement of components, it requires longer paths, degrading the conductivity of the trace. On the other hand, recent work in HCI research [88], discusses fully integrated woven circuitry as a research gap for future work, and highlights the opportunity to expand the woven circuit to integrate multi-material weaving practices into e-textiles.

2.3.2 Wire Materials. Different materials can be used to form connections, such as insulated copper-clad aluminium wires [31, 54]. The insulation adds an additional layer of protection against electrical issues. However, using rigid metallic wires as wefts negatively impacts the drapability and texture of the fabric [54]. While used in prior work [30, 31], this method can also lead to discrepancies in the woven structure [75], potentially compromising the electrical stability of the circuit [30, 91]. Alternatively, metallic or conductive yarns provide another option for weaving connection traces. These yarns are typically produced by wrapping a non-conductive, flexible core with a conductive metal [72]. One advantage of conductive yarn over insulated wires is its flexibility and texture, allowing it to blend seamlessly into the substrate structure and achieve more ubiquitous integration [10]. Recent research has explored options for fabricating biodegradable conductive threads [89] for low-fidelity e-textile prototyping. However, these environmentally conscious and sustainable practices face challenges such as replicability, lack of standardization, and inconsistent performance due to reliance on locally sourced materials and varying climate conditions. In our research comparing commercially-available options [5], we experimented with several types of conductive threads, including Adafruit stainless steel, silver-plated Karl Grimm, enamelled copper, and silver-plated Madeira. Among these, the silver-plated Madeira HC-12 ($<100\ \Omega/m$) provided the most reliable functional and aesthetic results for high-fidelity projects.

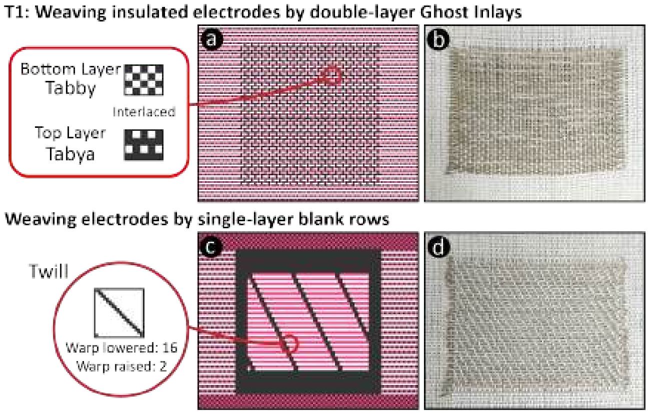

Figure 3: Electrode weaving with conductive thread: a) draft using T1 as a double-layer Ghost Inlay; b) woven fabric electrode using T1 (insulated from the back); c) draft using AdaCAD tutorial; d) resulting woven electrode.

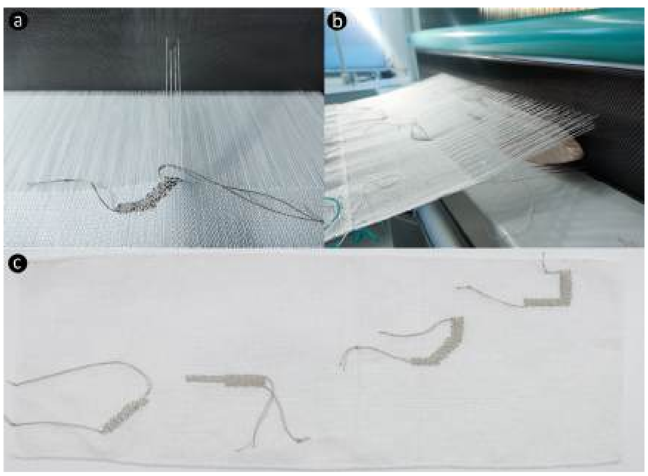

Figure 4: Using our T1 technique to weave a conductive thread electrode as a double layer Ghost Inlay showing the automation of the process alternating between the: a) top layer, b) bottom layer, and c) in a variety of angles an directions.

2.3.3 Circuit Components. Researchers have explored weaving e-textile sensors and actuators, but other electronic circuit components typically remain external to the fabric [13, 84]. One approach involves weaving a pattern with floating threads, which allows rigid parts to be placed through the *floats*, securing electronic components in place [24, 91]. Another approach is to position components between fabric layers, effectively forming a pocket to house them. Double weaving techniques can be used to form such structures, producing woven fabrics with two distinct layers [12, 13]. Prior work has also explored multi-layer weaving structures to store sensing components, serving as a protective shield against external hazards [58, 78, 84]. However, Jacquard double weaving in the middle of the fabric (away from the selvage) creates enclosed gaps, similar to closed pockets, once they are completely woven. This approach limits post-weaving integration of electrical components and offers minimal flexibility for troubleshooting and debugging. Researchers have suggested that future work should consider creating "flexible PCBs that can be customized into 2D shapes that align with the design [..] to create robust yet seamless circuit integration" [88] or "distribute electronic components into circuit islands that can be more seamlessly woven into the textile structure" [79].

3 WovenCircuits Fabrication Techniques

Weaving, in its most general application, typically involves throwing the shuttle (i.e., the weft yarn bobbin) across the entire warp width. This presents significant challenges when weaving circuit layouts where parallel connection traces must be effectively insulated from each other to prevent issues such as short circuits or signal cross-talk. To address this, we utilized parametric design tools (AdaCAD [16, 20]) on a digital Jacquard loom (TC2 [66]). Our design research produced hundreds of samples that informed three fabrication techniques for weaving insulated electrodes (T1), multi-layer pockets for electrical components (T2), and electric connections (T3) through WovenCircuits.

Research Through Design (RtD) Approach. Adopting an RtD approach as proposed by Zimmerman et al. [90], our exploration of WovenCircuits engages with the wicked problem of how to seamlessly embed circuit layouts and electronic components into woven textile substrates. This understanding of RtD suggests that contributions should be evaluated based on the rigour of the design process, the novelty of the invention, its relevance in addressing the problem, and its extensibility—that is, the extent to which it can be built upon in future work. Our design research process involved weaving more than 15m of 36cm wide fabric (totalling 5m^2) over the course of 18 months. This formed an annotated portfolio [21] of samplers, iterations of research products, failed attempts, and experiments (Figure 2). The following fabrication techniques, and subsequent characterization and fabrication workflow, emerged from this iterative process. Together, they form a collection of extensible methods that directly address the challenges of designing functional woven e-textiles, which we later demonstrate through six high-fidelity research artefacts.

3.1 T1: Weaving insulated electrodes using double-layer Ghost Inlays

To integrate electrodes into woven structures, conductive thread is commonly used as an inlay to form the conductive surface [78] (see Figure 3). Inlay weaving allows additional yarn, independent from the weaving structure, commonly referred to as a supplementary weft, to be manually integrated into the woven textile, enabling weavers to create intricate shapes [70]. Inlay weaving is considered labour-intensive and time-consuming [70], with a high barrier to entry for beginner weavers, especially on Dobby looms. Inlay weaving on Jacquard looms streamlines the process because individual warp threads can be lifted, allowing weavers to have more precise control over the placement of their supplementary weft [74].

The capabilities of computational weaving on Jacquard looms addresses this issue by introducing 'blank rows' at every other step, allowing the loom to alternate between the inlay warp ends and the background [16, 20]. However, this method creates the inlay on the same layer as the rest of the fabric. Since both the background and inlay exist on the same layer within the electrode area, each row of conductive thread is followed by a row of insulating non-conductive thread, reducing the electrode's surface area and thereby degrading its efficiency (see Figure 3d). Additionally, this approach makes the electrode conductive on both sides of the fabric, which restricts its use in wearable applications due to the potential for false positive touches caused by contact with human skin.

To solve this, we built upon previous work on multi-layer weaving structures [74] by developing the technique of 'Ghost Inlays', which introduces a weaving structure that incorporates blank rows at every other step, hidden in a double weaving block we call 'Tabya', as seen in Figure 3a. This effectively combines double weaving with inlay weaving by instructing the loom to weave a bottom layer (the background and main weave structure) and a top layer (an inlay woven with the supplementary weft) at the same time (Figure 4). Implementing Ghost Inlays gives a clearer visual guide on where the electrode area is (Figure 4a) because only the warp threads of the top layer are lifted, compared to inlays with pick-up sticks (on Dobby looms). This techniques also resolves the issue of single-layer inlays (on Jacquard looms), making it more suitable for wearable applications because the bottom layer insulates the conductive material on the top layer.

Following this approach, the Ghost Inlays technique has the benefits of being: 1) insulated from the back in a double-layer structure, which is more appropriate for wearable and on-skin interfaces; 2) more conductive, as there is more surface area of conductive thread on the top layer; 3) independent from the weft yarn used in the base fabric, allowing parallel conductive traces to be woven at the same step without sharing the same weft; and 4) more visually clear and customizable since the process is guided by the weaving draft, resulting in neater inlay and trace salvages.

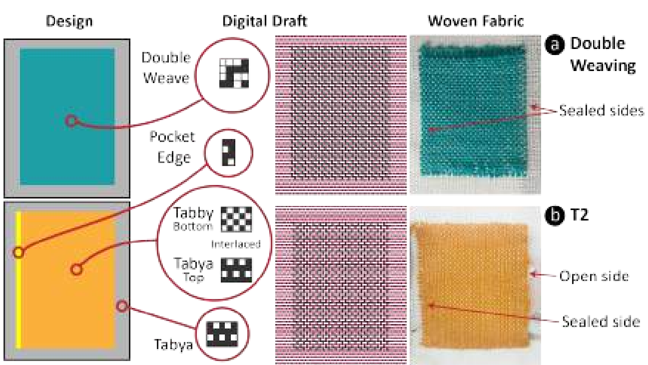

Figure 5: Woven pockets using: a) double weaving and b) the WovenCircuits T2 method as a single-sided pocket.

3.2 T2: Integrating electronic components into single-sided pockets

Pockets are areas with double weaving structures designed to double the fabric's width or hide objects within two or more layers [73]. These pockets can be employed to conceal electronic components effectively. Double weaving of closed pockets (with sealed edges on all sides) requires the integration of components during the weaving process, limiting their maintenance, removal, or replacement post-weaving (see Figure 5a). To address this, we developed the 'single-sided pocket' technique.

The top and bottom edges of a pocket (parallel to the weft) are sealed in all cases due to the continuous interlacing of the warp threads, which connect the edges of the top and bottom sides to the background layer. Applying our 'Tabya' block to the area generates open sides by default for the weft-parallel sides as the outermost warp thread is isolated from adjacent warp threads, preventing their interlacement and thus creating openings. To control whether a side is opened or closed, we introduce a pattern at the edge of the pocket that needs to be closed i.e. 'pocket edge' (see Figure 5b). This pattern interlaces the outermost warp thread of the top layer with the adjacent warp thread of the bottom layer, selectively closing this side. The single-sided pocket technique allows for the easy removal of components after weaving, which is essential for in-situ reprogramming, repairs, and washability. Pockets designed to house components must also consider yarn shrinkage after washing and be appropriately sized for the shape and topology of the components. Dimensions should take the component's height into consideration, in addition to its area (L×W), to match their real-life sizes and ensure accurate pocket sizing.

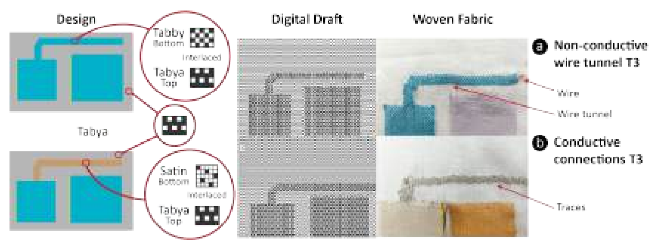

Figure 6: Woven electric connections using our WovenCircuits T3 method as: a) non-conductive wire tunnels and b) conductive thread traces.

3.3 T3: Weaving electric connections with conductive thread traces and wire tunnels

Connection traces (paths that link circuit components) can be created by weaving strands of conductive thread parallel to either the weft or the warp. However, this approach may not be suitable for implementing complex circuits. Our technique enables free-form connection traces, allowing them to continue horizontally, vertically, and/or diagonally as double weaving structures using either conductive or non-conductive thread. Using conductive thread, electrical connections can be visible from the front but insulated from the back side of the fabric. With non-conductive thread, the result is an insulated tunnel that can hide electrical wires (such as copper-core insulated wires), see Figure 6. Both options allow the conductive trace to be implemented in variable size, which can be used to optimize the electrical resistance of the path.

Horizontal Connections. We experimented with various methods of weaving conductive threads as traces and found that the first and last woven threads (entry and exit points) should be positioned

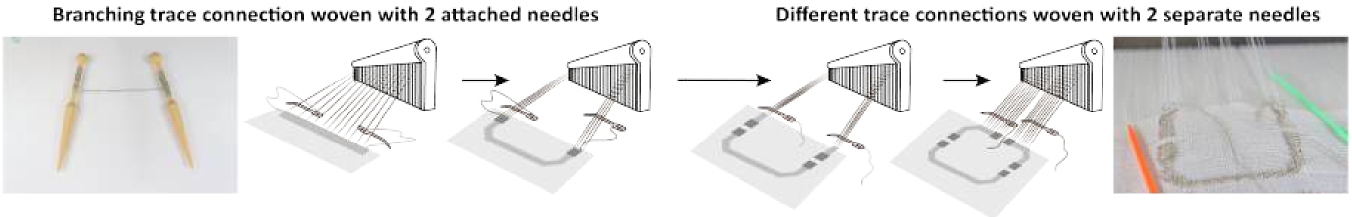

Figure 7: Weaving U-shaped (branching) traces with two attached needles versus isolated traces with two separate needles.

on opposite sides to effectively connect two distant components. To achieve this setup, horizontal traces must be designed with the height of an odd number of pixels (steps). However, since trace areas employ two layers, weaving steps are shared between both layers. For example, if a trace is designed with a height of 10 pixels, it will appear as 5 pixels in the conductive woven fabric. Therefore, to successfully weave a trace with a height of n steps, where n is an odd number, the trace must be designed with a height of $2n$ pixels.

Vertical Connections. Since weaving structures do not fill areas uniformly for each weaving row, we recommend choosing a weave structure without long floats for conductive vertical traces. A wider trace, such as 6 pixels wide, has proven to reduce the likelihood of failed steps during the weaving process.

U-shaped Connections. In our technique, we follow circuit design guidelines used in previous research [22] on spacing, crossings, and proper connection. For instance, we recommend weaving U-shaped traces using a single conductive thread, starting at the middle of the thread rather than with one loose end, preventing discontinuity. Since weaving progresses from the bottom up, the horizontal part of the U-shape should be woven first (starting from the middle of the thread), with two tapestry needles attached to the two ends, which are then woven in parallel after the branching occurs (Figure 7).

Crossing Traces. Crossing traces in circuit routing occurs when two or more traces intersect on the same layer, which can result in short circuits and cross-talk between different nodes [22]. This can be addressed in three ways: 1) redesign the circuit to avoid crossovers, 2) using insulation methods such as via stitching [34], or 3) employing multi-layer weaving structures. In the latter approach, the traces at the intersection can be insulated from one another by re-routing the traces to the top and bottom layers.

4 Characterization

To further understand WovenCircuits, we characterized the electrical behaviour and the washability effect of different woven structures. We conducted a series of experiments to quantify relevant design factors. The identified factors are the sizes of the traces designed (F1), the weaving structure drafted (F2), and the yarn ply or number of strands used in weaving (F3). These design factors enable customization at the three steps of the fabrication process, where they can be manipulated at Step 1 (designing the circuit), Step 2 (generating the weaving draft), and Step 3 (weaving the fabric circuit) respectively. Each of these factors can be broken down into both: 1-dimensional traces (lines, linear connection traces across weft), 2-dimensional traces (areas, regions of contact L×W or weft×warp), and the effects of laundering on resistance and dimensions of both.

Each experiment was repeated (i.e. re-woven with the same variables) five times for average measures and the resistance was measured using an AstroAI AM33D multimeter. Additionally, we followed established guidelines on the launderability of e-textiles [60] to inform our washing procedures in this experiment. All experiments were washed four times on a delicate cycle with cold water and no spin in a domestic washing machine (Samsung Electrolux NS28262). After each wash, when the fabric has completely air dried, we measured the resistance and trace dimensions under each design factor using the same multimeter. This characterization is to guide digital weaving practitioners and researchers of e-textiles with desired properties of customized woven circuits.

All experiments were woven on a 660 end (45 EPI) TC2 digital Jacquard loom. Both the warp and weft of the non-conductive woven fabric were implemented using 100% mercerized cotton 2/20. We tested several types of commercially available conductive threads, with silver-plated Madeira HC-12 (<100Ω/m) providing the best functional and aesthetic effect [5]. Our results reflect these specific loom and warp settings; variations in these parameters may influence outcomes and should be considered in related applications.

4.1 F1: Designing Trace Sizes (at Step 1)

The dimensions of connection traces has a direct impact on the electrical performance of the circuit [4]. This design factor can be selected and altered during the design step. We conducted various trials to evaluate the performance of woven connection traces using our fabrication method, examining their effectiveness across both wefts (lines) and warps (area).

4.1.1 Line. To understand how trace size impacts conductivity, we compared the resistance of four line thicknesses. We wove 10 *cm* long traces, each with a distinct line thickness: 2 *mm*, 3 *mm*, 5 *mm*, and 6 *mm*. All traces were woven using a twill structure (Figure 8). Each line thickness was woven five times under the same conditions. The resistance of each trace was measured and documented, and the average resistance for each size was calculated (Table 1). The results indicated that at 3 *mm* thickness (and above), the average resistance drops and stabilizes around 0.55 Ω. However, for traces thicker than 3 *mm*, the change in resistance is negligible, making the additional consumption of material and space unnecessary.

4.1.2 Area. Areas serve as the primary contact points between external elements and the rest of the connected traces. Therefore, increasing the size of area traces may be desirable for different applications. To understand the relationship between area size and

Table 1: Resistance Characterization: WovenCircuits woven with conductive thread in different sizes (F1).

Trace Type	Width/Size	Resistance (Ω)
Line (Length = 100 mm)	2 mm	1.07
	3 mm	0.55
	5 mm	0.54
	6 mm	0.58
Area	3×3 mm^2	0.71
	6×6 mm^2	0.94
	8×8 mm^2	1.13
	10×10 mm^2	1.91

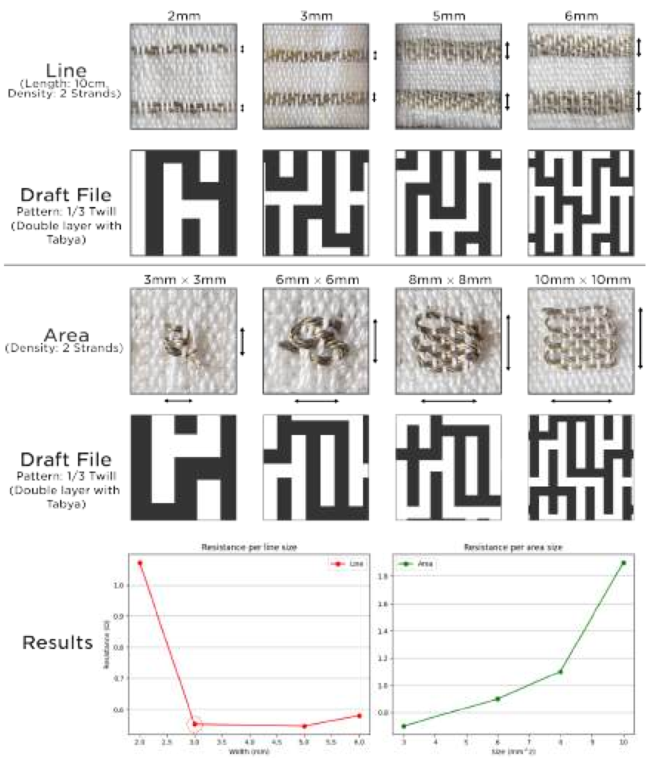

Figure 8: Resistance Characterization: The effect of trace size (F1) on electrical conductivity for line and area traces, highlighting the optimal balance between resistance and material-consumption (circled).

conductivity, we measured the resistance of area traces of various sizes, ranging from 3×3 mm^2 to 10×10 mm^2 (see Table 1). We found that resistance is directly proportional to area size, meaning that larger area traces experience higher resistance values, as shown in Figure 8. Hence, it is recommended to design area traces with the smallest, most efficient sizes appropriate for the specific application.

4.1.3 Washability. The resistance of line traces steadily decreases after each wash, indicating a change in conductivity with repeated laundering. In contrast, the resistance of area traces decreases over the first two washes but remains consistent thereafter (Figure 9). For trace dimensions, both line and area traces maintain a consistent length (no horizontal shrinkage) before and after washing. However, the height of the traces decreases by an average of 24% line traces and 12% for area traces after the first wash and then stabilizes, remaining relatively consistent with each subsequent wash.

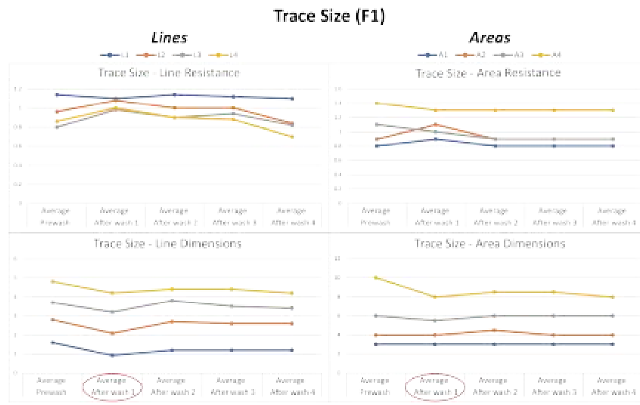

Figure 9: Washability Characterization: Trace size (F1) impact on resistance and dimensions (mm) after washing.

4.2 F2: Drafting Weaving Structures (at Step 2)

HCI researchers have explored various weaving structures to develop fabrics with integrated sensors [12]. This design factor can be modified during Step 2 (generating the weaving draft) without necessarily changing the visual design or affecting the weaving process on the loom. We characterized the effect of different weaving structures on electrical behaviour by testing four patterns: tabby, twill, satin, and shaded satin. Connection traces were woven using our fabrication method across both wefts (lines) and warps (areas).

4.2.1 Line. To characterize the weaving structures of line traces, we wove 10 cm long traces, each incorporating a unique weaving structure for the top layer of the Ghost Inlay, as shown in Figure 10. The plain weave structure (tabby), which has the least number of floats, exhibited the highest resistance value of 3.16 Ω due to its narrower spaces and tight interlacement. Comparatively, other weaving structures with a higher number of weft floats showed lower resistance values, with the satin exhibiting 0.59 Ω as the optimal compromise versus material consumption.

4.2.2 Area. To understand electric resistance of weaving structures in area traces, we drafted and wove square shapes of equal size 8×8 mm^2 using the four different patterns. Measurements were taken across the diagonal of each area trace, see Figure 10. The tabby pattern resulted in the highest measured resistance of 1.42 Ω, while resistance values steadily decline with patterns that have a higher number of floats, such as satin at 0.68 Ω and shaded-satin 0.63 Ω, as shown in Table 2. Since weaving with shaded satin is more material-demanding, we concluded that satin is the most efficient pattern for connection areas in terms of conductivity. However, for specific sensing applications, shaded satin might be preferred based on other factors, such as exposed surface area, which could take precedence over material consumption.

Table 2: Resistance Characterization: WovenCircuits woven with conductive thread with different weave structures (F2).

Trace Type	Weaving Structure	Resistance (Ω)
Line (Length = 100 mm)	Tabby	3.16
	1/3 Twill	0.74
	5-end Satin	0.593
	7-end Shaded Satin	0.58
Area	Tabby	1.42
	1/3 Twill	0.75
	5-end Satin	0.69
	7-end Shaded Satin	0.63

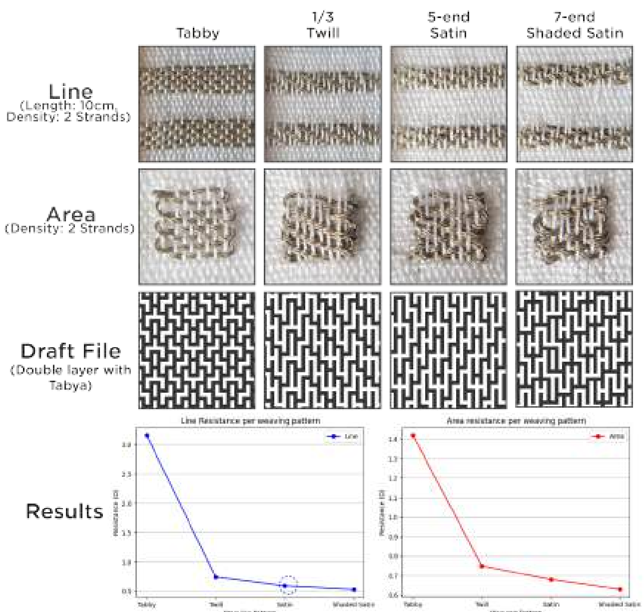

Figure 10: Resistance Characterization: The effect of weaving structure (F2) on electrical conductivity for line and area traces, highlighting the optimal balance between resistance and material-consumption (circled).

4.2.3 *Washability.* Overall, resistance decreases for both line and area traces after each wash (Figure 11). Most notably, the tabby structure exhibits a resistance that is, on average, 70% higher than other structures and decreases at a rate of 12%. This rate is significantly higher than the average decrease of 7% observed in other structures, rendering the latter almost negligible in comparison. Area traces follow a similar pattern but on a smaller scale. Additionally, the dimensions of both line and area traces remain stable in length, with no horizontal shrinkage, though the height decreases by 6% for area traces after the first wash and then stabilizes.

4.3 F3: Weaving with Multiple Strands (at Step 3)

Changing the cross-sectional area of the conductive thread can impact the trace conductivity. This design factor can be adjusted during the final step (weaving the fabric on the loom) without altering the visual design or draft files. To characterize the electrical

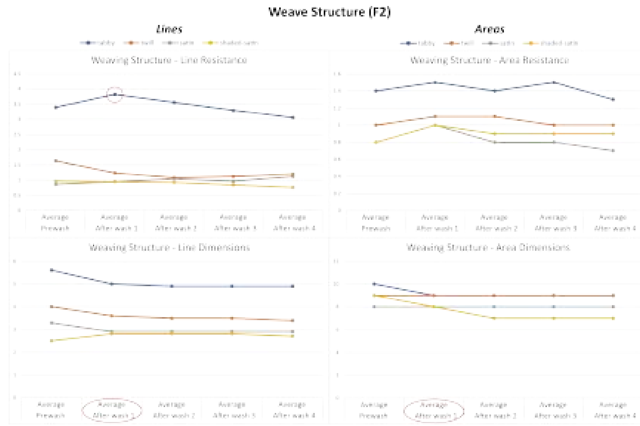

Figure 11: Washability Characterization: Weave structure (F2) impact on resistance and dimensions (in mm) after washing.

behaviour of WovenCircuits without changing the dimensions or structure of the designed trace, we compared the resistance of multiple stands of conductive thread across lines and area traces.

4.3.1 *Line.* We wove four line traces, each using a different number of strands of conductive thread (ranging from 1 to 4) until we reached saturation. The trace dimensions were fixed at 10×0.5 cm^2, and the weaving structure consistently tabby, with each configuration repeated five times. Using a single strand of conductive thread resulted in the highest average resistance of 0.85 Ω. However, resistance steadily decreased as we increase the number of strands, reaching 0.45 Ω with the 4-strand conductive thread (Table 3). This reduction in resistance is due to an increase in the cross-sectional area of the conductive thread and the corresponding decrease in non-conductive spaces within the trace itself (Figure 12).

Table 3: Resistance Characterization: WovenCircuits woven with conductive thread with multiple strands (F3).

Trace Type	Width/Size	Strands	Resistance (Ω)
Line (L = 100 mm)	8 mm	1	0.853
		2	0.56
		3	0.48
		4	0.45
Area	10×10 mm^2	1	2.73
		2	1.50
		3	0.827
		4	0.813

4.3.2 *Area.* We compared the number of strands in a surface area by fixing the size at 8×8 mm^2 (Figure 12). Similar to line traces, areas show a decrease in resistance with more strands, as fewer non-conductive spaces result in larger conductive cross-sections. The maximum resistance measured was 2.7 Ω using one strand of Madeira HC-12, while the minimum resistance of 0.8 Ω plateaus using 3 or more strands (Table 3). Hence, a 3-strand conductive thread can be considered the most efficient for area traces.

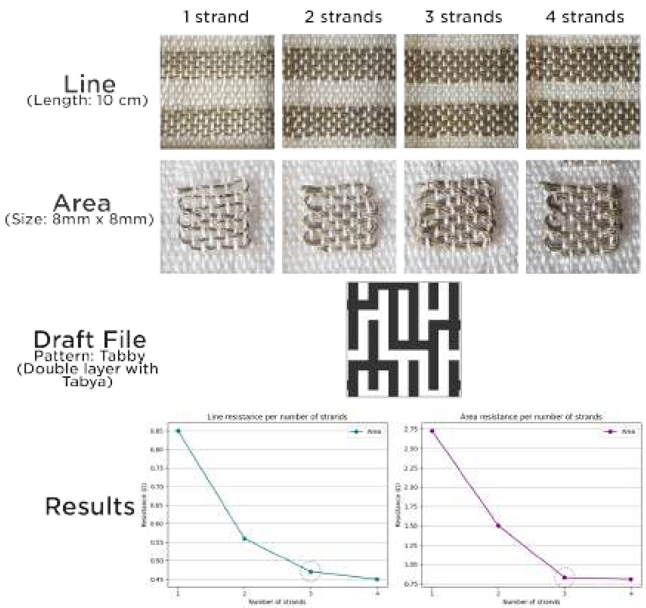

Figure 12: Resistance Characterization: The effect of number of strands (F3) on electrical conductivity for line and area traces, highlighting the optimal balance between resistance and material-consumption (circled)

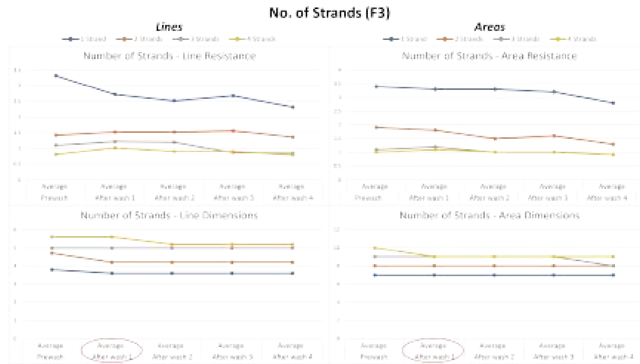

Figure 13: Washability Characterization: Yarn ply (F3) impact on resistance and dimensions (in mm) after washing.

4.3.3 Washability. The overall trace resistance decreases after each wash for both line and area traces (Figure 13). Similar to the observation made with using a tabby pattern, line traces made with a single strand have a higher average resistance compared to those using multiple strands, 58% on average, but their resistance decreases at a higher rate. Specifically, the resistance of single-strand line traces decreases at a rate of 20%, whereas the resistance of multi-strand traces decreases by an average of 4%. A similar pattern is observed with area traces. The dimensions remain consistent across the trace length, but the height decreases by 3% for area traces after the first wash, followed by consistent and steady measurements thereafter.

5 The 3-Step Fabrication Process

The main outcome of our RtD exploration is understanding and reverse-engineering a step-by-step way of designing woven circuits. The process of fabricating WovenCircuits (presented below) is versatile and customizable, allowing designers to leverage the use of computational looms (i.e. digital prototyping weaving machines) utilized in recent work [16, 20, 83].

5.1 Step 1: Designing the circuit

The initial step involves designing the electric circuit, which includes determining the placement of each component with accurate dimensions and placeholder connections. In our work, we used an open-source circuit design CAD tool (DipTrace) with debugging capabilities to ensure thorough testing before weaving. The next step is to create a graphical representation of the circuit at a 1:1 scale, incorporating design factors such as colour (representing blocks of weaving structure), shapes, and dimensions of both functional and aesthetic elements. Colours are used as markers for different areas, which will later be assigned specific weaving structures.

A vector design editor, such as Adobe Illustrator, is used to generate the required graphical representation with a translation of units between the design (PPI: pixels per inch) and woven structure (EPI: ends per inch). To avoid a stretched height caused by the aspect ratio asymmetry of different units, we found that dividing the design file height by 1.87% effectively squeezes it back to the expected dimensions. This step also requires weavers to decide on their selection of inert yarns, SETT (warp yarn per inch), and project warp yardage.

5.2 Step 2: Generating the weaving draft

A weaving draft file contains the information that a computational loom needs to produce the intended designs [16, 20]. We experimented with two approaches for producing weaving drafts: image-based and parametric-based. Creating image-based draft files for weaving (e.g., using Photoshop) has been widely adopted in the digital weaving community. However, recent parametric design tools (i.e. AdaCAD) [10, 12, 20] offer greater freedom, creative control, and customization over weaving structures. Nonetheless, a detailed description of the process and differences between both approaches is provided in the supplementary document. In this step, we apply weaving structures to colour-coded regions of the circuit by translating the vector design on Adobe Illustrator to the loom software using AdaCAD, see Figure 14. This is the step where we apply the WovenCircuits techniques described above, using them as a painting palette to decide where to apply Ghost Inlays (T1) and single-sided pockets (T2) while adhering to the considerations for weaving electric connections (T3).

5.3 Step 3: Weaving the fabric circuit

To weave the circuit design, simple shapes can be printed on paper for use on a floor loom, allowing WovenCircuits to be implemented as inlays using pick-up sticks. However, computational Jacquard looms can partially automate our fabrication techniques (T1, T2), reducing the time and labour required by up to 90%.

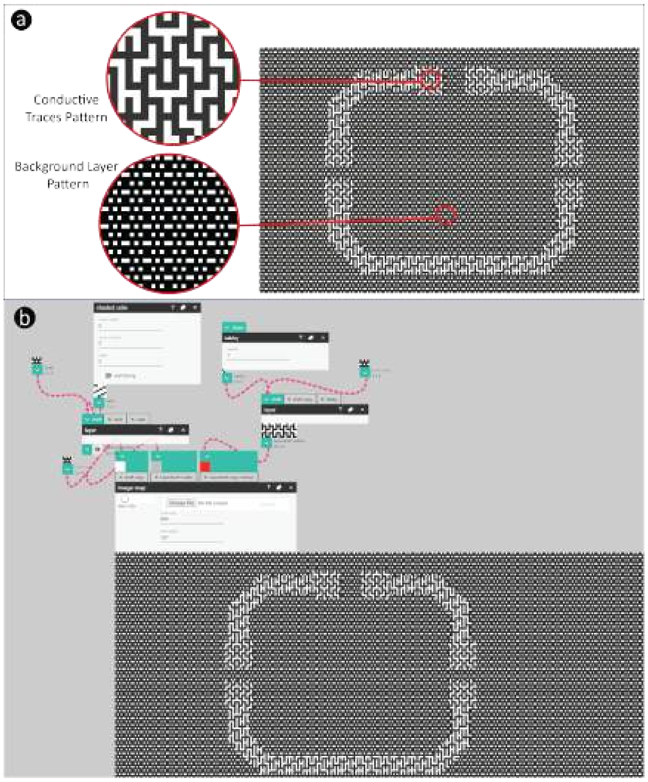

Figure 14: AdaCAD Design Environment: a) close-up on the resulting weaving structure, which compares background and ghost inlay layers; b) draft design process in AdaCAD.

6 Applications

One of the outcomes of our RtD [90] approach is a set of research artefacts built using our 3-step fabrication process and fabrication techniques. They feature a diverse range of designs, including wearable garments, bags, and everyday objects integrated into environments such as tables, chairs, floors, and walls.

6.1 PowerPocket Jeans for Wireless Charging

To demonstrate a fully woven circuit for wearable applications, we designed the PowerPocket as a woven wireless charger created using the T2 and T3 techniques. The PowerPocket is sewn onto the inside of the back pocket of a pair of jeans (see Figure 15). The user can charge their smartphone device by simply placing it in that pocket. The PowerPocket is woven with cotton 2/20 for warp and bottom layer weft, while the top layer weft is woven with cotton 8/20 in three different colours and Madeira HC-12 conductive thread for trace connections. Measuring 17×10 *cm*, the circuit incorporates a 5V 2A wireless transmitter coil. The insulated coil can deliver up to 10 watts of power to the receiving device. Power is supplied by a 3.7V LiPo battery, a Trinket microcontroller (22×15 *mm*), and a voltage step-up module (to 9V). We successfully tested the wireless charging functionality with an iPhone and Apple Watch. The circuit also includes a sewable power switch to give users control of when to turn it ON/OFF. All other components are easily removable from their housing (T2) for laundering and maintenance. Users also have the flexibility to either proudly display their woven circuit as expressive clothing [47] or conceal it by attaching the denim pocket using snap fasteners. The latter preserves the look and feel of a typical everyday jeans back pocket, while adding extra functionality extending work on interactive pockets [77] and pants [69, 72].

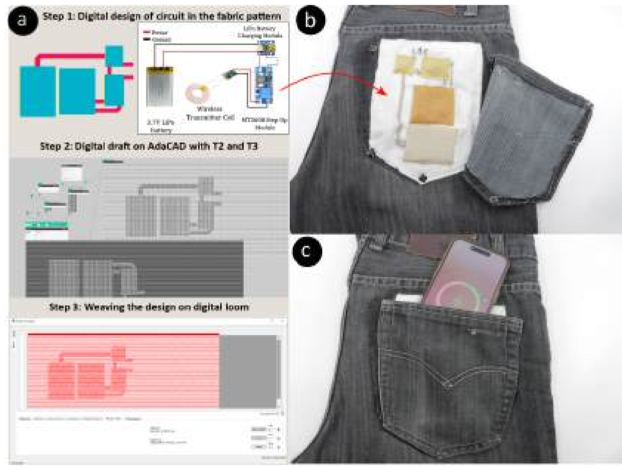

Figure 15: Design and implementation process for the PowerPocket Jeans showing the fabrication steps (a), the woven circuit (b), and wireless charging with an iPhone (c).

6.2 Thermo-Placemat for Warming Food

The Thermo-Placement was created using the T1 technique of double-layer Ghost Inlays. This placemat, with dimensions 24×36 *cm* (cotton 2/20 for the warp and bottom layer weft), has the ability to keep food warm (see Figure 16). We wove Madeira HC-12 conductive thread into the bottom layer of the centre inlay pattern while using regular yarn for the top layer weft (cotton 8/20). We used a 4x4 twill weaving structure for the Ghost Inlay sections, alternating between two colours for visual appeal. For the background, we used the waffle-ish pattern to give the placemat a sturdy, durable drape with varying textures. We envision the Thermo-Placemat can be coupled with interactive tableware [61] and ceramic ware [87].

In addition to the conductive inlay, the user can choose to use the pocket created from the 2-layer structure to house an insulated heating pad to warm up their food. In both cases, this placemat can support playful and mindful interaction while engaging with food with or without utensils [42, 43].

6.3 GoGreen Backpack for Embodied Expression

To show a circuit hidden within woven fabric, we created a motif that integrates electric connections, input, and output in a completely discrete way. Inspired by efforts for climate action, the woven piece (17×36 *cm*) features a cityscape with buildings that light up dynamically, symbolizing the vibrancy of urban life (see Figure 17). When the woven bicycle icon is touched, the lights activate, highlighting the importance of sustainable eco-friendly

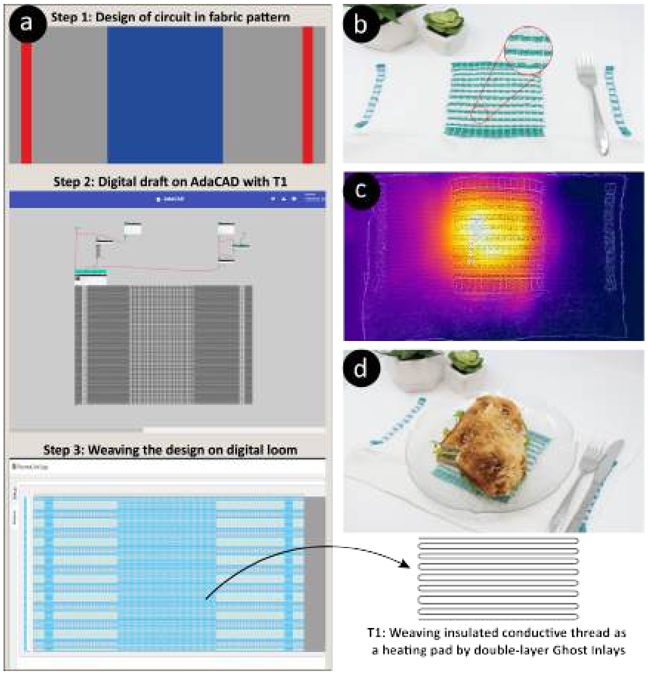

Figure 16: Design and implementation process for the Thermo-Placemat showing the fabrication steps (a), the woven circuit (b), a heat map image (c), and the placemat keeping a plate of food warm (d).

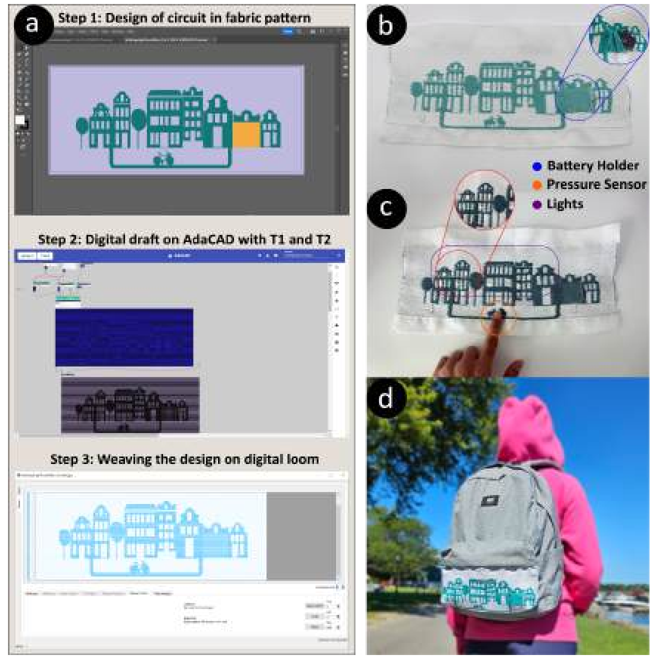

Figure 17: Design and implementation process for the GoGreen Backpack showing the fabrication steps (a), the woven circuit (b), the interaction with the bicycle pressure sensor, lighting up the city scene (c), and the backpack being worn in-the-wild (d).

transportation in combating climate change. After weaving the fabric circuit, we used it to sew an external compartment on a backpack that allows users to be proud of their supported cause. This application uses the T1 and T2 techniques of weaving insulated electrodes and pockets for housing the sewable battery holder.

We wove Madeira HC-12 conductive thread in the bottom of the center inlay (featuring the bicycle as the key design element) for a pressure sensor acting as the circuit switch. We used a tabby weaving structure for the line traces (T1) and pockets (T2) and integrated seven sewable LEDs in some 'windows' to light up as the photonic actuation. The piece is also woven in a two-pick structure, a weaving technique where two picks are inserted between each row of warp [70], facilitating the creation of multi-colour designs by alternating between shuttles repeatedly for each top-layer weaving step. We used a cotton 2/20 warp and cotton 8/20 yarn for both the top and bottom layer weft. We envision this design can be used for functional purposes (such as lighting up a dark backpack compartment when opened up to help see inside) or experiential purposes (such as self-expression and raising public awareness [25] with its actuation effect [50]).

6.4 VibroChair Cover for Posture-Correction

WovenCircuits can be designed in curves and aesthetic shapes beyond geometrical straight lines like a PCB. To explore this, we created a fabric chair cover, that can be retrofitted for existing office or dining furniture, with WovenCircuits seamlessly integrating a complete circuit (see Figure 18). This application helps users correct

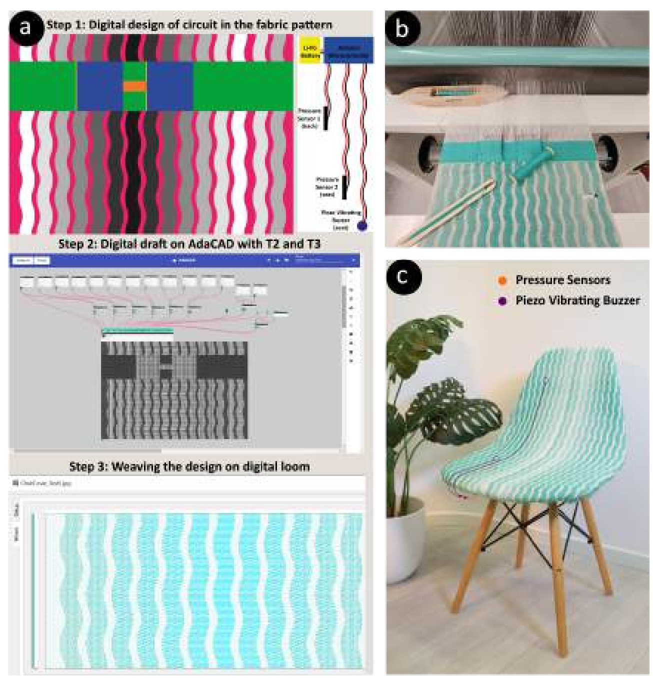

Figure 18: Design and implementation process for the VibroChair showing the fabrication steps (a), the fabric as it is being woven (b), and the VibroChair (c).

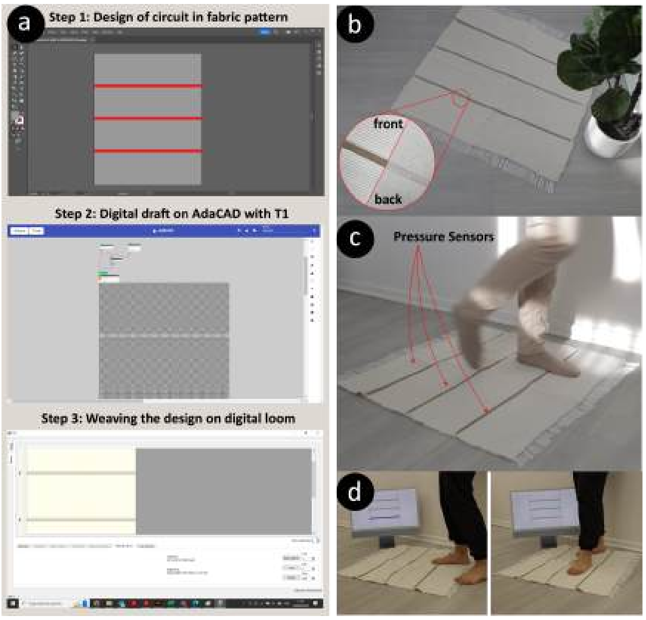

Figure 19: Design and implementation process for the SensingRug showing the fabrication steps (a), the woven rug (b, c), and the interaction with the SensingRug (d).

their posture by subtly alerting them when they are not sitting up straight [45]. Our VibroChair Cover comprises two woven fabrics (80×36 *cm* each) sewn together across the salvage seam and sewn to an elastic chair cover for easy removal. It uses the T3 technique of weaving wire tunnels to conceal (in curvy waves) two pressure sensing spots and a small piezo motor that vibrates when sitting is detected with no leaning back. We used cotton 2/20 yarn for the warp, cotton 8/20 yarn for the top and bottom layer weft, and Madeira HC-12 conductive thread for all connections. Our application also uses T2 to integrate the microcontroller and battery into single-sided pockets at the edge of the fabric. This extends previous work on interactive chairs [6, 62] where electronic components are attached to the chair itself, allowing the customization of woven chair covers to add interactivity to existing chairs.

6.5 SensingRug for Activity Recognition

WovenCircuits can be integrated within everyday fabric objects around homes to capture natural interactions people are performing in their daily lives. For example, we can detect when a user sits on a sofa or bed for too long or steps or falls on the floor carpet. To explore this, we created the SensingRug, a 70×75 *cm* rug with tassels that can detect when someone steps on different parts of it. This application resembles a Boho handwoven bathroom rug or floor mat featuring natural colours (weight 5 weft yarn). We used WovenCircuits to seamlessly integrate a sensor circuit (see Figure 19). Our SensingRug uses the T1 technique of weaving insulated electrodes (with Ghost Inlays) in three touch sensing spots, detecting when users step on it (barefoot or with socks on). These touch points are made with Madeira HC-12 conductive thread on the top layer weft and cotton 8/20 yarn for the bottom layer weft. This extends previous work on woven sensor swatches [12] where a full-scale object is fabricated with the sensors, allowing the seamless integration of interactivity into real-world things.

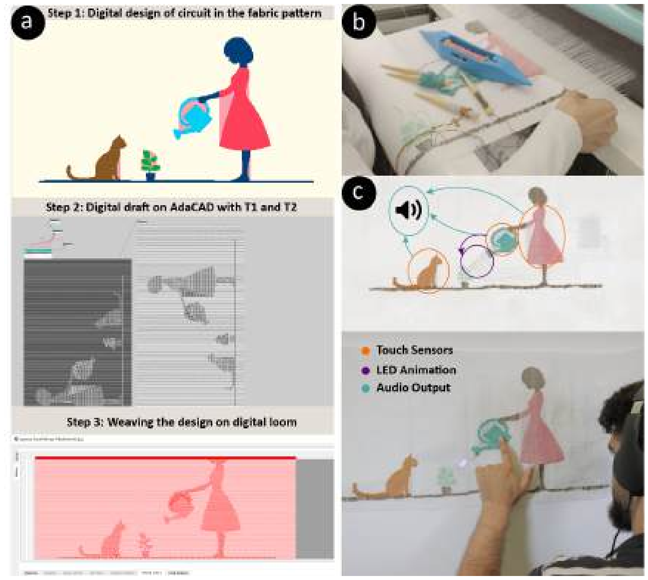

Figure 20: Design and implementation process for the ThirstyCat Tapestry showing the fabrication steps (a), the woven circuit (b, c), and the interaction with the tapestry (d).

6.6 ThirstyCat Tapestry for Tactile Animation

To explore woven tapestries, we designed an interactive one that combines auditory and visual experiences with tactile interactions. Our wall-mounted tapestry measures at 36×97 *cm* and features a story scene with three main characters (interactive elements): a woman, a cat, and a watering can for a potted plant (see Figure 20). Each of these elements functions as a capacitive touch sensor, woven using the T1 and T2 techniques and connected to a Bare Conductive Touch Board microcontroller. When the user interacts with these elements, the tapestry animates the sewable LEDs and responds with audio outputs such as a meow, waterfall sound, and the speaking woman's voice. We applied the T1 double weaving technique with Ghost Inlays to the three elements in conjunction with T2. Additionally, we inverted the pattern for 'background' areas around the elements to workaround the branching-out curves. For example, the watering can was colour-coded as a block with two colours: pink for the background colour and blue for the watering can, as seen in Figure 20. We applied the inverse of the T1 pattern to the pink areas so that the background colour (white) would rise to the surface, allowing the watering can to be woven with a single continuous conductive thread. This approach avoids segmenting the sensor into disconnected sections, ensuring it functions as one piece. We discuss this workaround more thoroughly in Section 7.6. This tapestry was inspired by previous work on woven interactive tapestries [13] and e-textile storytelling crafting [71]. The tapestry uses cotton 2/20 for the warp and bottom layer weft, while the top layer weft was woven with textured and coloured conductive yarns [33] made from cotton 8/20 yarn.

7 Discussion, Limitations, and Future Work

Below, we reflect on the unique properties of WovenCircuits through a qualitative perspective of its contribution, comparing it to and building on existing literature.

7.1 Customizability of Circuit Design

Through iterative experimentation, WovenCircuits demonstrates how weaving can move beyond grid-like, rectangular patterns [46, 79] toward supporting free-form shapes, offering greater expressiveness and customization. The scalability of conductivity (F2), exemplified in high-power applications such as the PowerPocket Jeans, shows the ability to support power-intensive circuits. Inlay and double weaving methods [13] incorporate non-conductive threads in parallel with conductive ones, creating gaps that degrade conductivity. By isolating electrodes within a non-conductive layer, WovenCircuits eliminates these gaps, significantly enhancing conductivity and reducing overheating and fire risks. These findings extend the landscape of woven interface design by offering an approach to woven circuit fabrication that is reproducible and invites designers and researchers to experiment with textile-based interactivity in everyday contexts.

Furthermore, literature on woven interfaces [88] has called for further hardware integration for seamless woven circuitry, suggesting approaches like flexible PCBs tailored to 2D shapes. While WovenCircuits demonstrates prototyping capabilities for integrated circuits, bulky components (e.g., motors or screens) remain a limitation shared across similar interfaces [88].

7.2 Automation and Control of Woven Circuit Fabrication

Previous work [46] highlighted the value of using digital Jacquard looms to automate the process of creating woven interfaces, providing advantages in scalability, customizability, and speed. This approach also empowered designers with creative freedom to hide or reveal circuit components within expressive and aesthetic designs. Additionally, it enabled scaling up final designs, building on the literature's knowledge of weaving swatches [9, 29, 53], patches [8, 46], and bits [37, 38] for broader usage.

Computational design and digital looms offer selective control over warp ends, eliminating constraints related to pattern implementation. However, the current digital weaving process is not optimized for e-textile applications. WovenCircuits was explored to capitalize on the advantages offered by computational looms, which are increasingly prevalent in the HCI and maker communities. State-of-the-art digital weaving machines, such as the TC2 [66], can be expensive (starting at €12,000 for a 1-Wide), but still within the range of small laser cutters. This enables both creative experimentation by hand and scalable manufacturing [79]. Our 3-step process relies on existing software tools [16, 20] that can be expanded to better support circuit design and their weaving drafts. This approach fosters expressive creations during the crafting process, where adjustments can be made on-the-fly in any of the three steps. Similarly, the three design factors can be altered throughout the process, allowing creators to intuitively make customizations, similar to the flexibility found in sewing practices.

As a form of co-production [15, 20] between the maker, machine, tools, and materials, we sought to streamline the process for makers of all skill levels, from novice to expert. By offloading production to the machine, makers can instead focus their efforts on using digital tools to create personalized, unique designs. This approach builds on previous work that encourages engagement with hand tools, such as using tapestry-needles as shuttles [79]. To make our work more accessible and replicable, we also opted to make use of off-the-shelf sewable e-textile components (such as sewable LEDs, battery holders, and microcontrollers) that are typically used for hand-stitching e-textile circuits. In contrast, using custom PCBs would sacrifice replicability and accessibility to maker communities.

7.3 Supporting High-Fidelity Prototyping

Low-fidelity prototyping, characterized by rapid swatch fabrication, has been a focus of e-textile research [13, 73, 88], where deployable applications have not received the same level of attention [31]. In contrast, our work advances high-fidelity prototyping, enabling the creation of fully integrated woven circuits. Our range of potential applications showcases high-fidelity research products that not only support functional interaction (sensing and/or actuation) but also embellish everyday things and expressivity.

While previous work recommends early-phase, low-fidelity prototyping processes in e-textile design to create "many swatches" that are "rapidly fabricated" [89], our approach supports high-fidelity prototyping of complete woven circuits. Our sample applications demonstrate the capabilities of WovenCircuits, which can be used in combination with other tools, such as Loom Pedals [83], or sustainable materials like EcoThreads [89] and BioFibers [49] for creating biodegradable woven e-textiles. This shift to high-fidelity prototyping repositions e-textiles from temporary research products to fully realized design artefacts.

Future research could also benefit from exploring applications of WovenCircuits in the context of 3D weaving [27, 81, 82], with the opportunity of interdisciplinary collaboration with 3D weaving specialists. While WovenCircuits is demonstrated through 2D Jacquard weaving, 3D weaving techniques could unlock new structural opportunities in woven circuits and shape-changing textiles. However, current 3D weaving techniques require the use of industrial Jacquard looms [27], which are often inaccessible to many makerspaces in comparison to smaller scale digital Jacquard looms like the one we used to synthesize this work. This creates an opportunity for researchers, designers, and practitioners to use the WovenCircuits 3-step workflow, and potentially its techniques (T1–T3), to explore other weaving applications such as 3D weaving.

7.4 Connectors as Functional and Aesthetic Elements in Woven E-textiles

Circuit components, such as connection traces and microcontrollers, have been identified by previous work [41, 79, 88] as a "limitation of [woven] interface research" due to their rigid nature. Inspired by research on creating woven circuits as "2D shapes that align with the design" [88] and distributing electronic components into "circuit islands" [79], WovenCircuits enables seamless integration of these components into the fabric's structure.

Previous work focused on weaving the sensing or actuating elements while rigid components are treated as external parts [12, 78, 84], often relying on extended wires for connections [30, 31, 58], or using components with a small footprint [30, 31] and employing weaving structures to hide components [13, 51]. However, WovenCircuits integrates circuit components directly into the fabric and offers flexibility in terms of weave structure, yarn type, weight, and colour for the top layer of component pockets. Unlike other approaches, WovenCircuits treats connections as integral aesthetic elements without compromising functionality.

7.5 Washability, Durability, and Longevity

To ensure the longevity of woven circuits, rigid off-the-shelf components can be designed for easy removal. By using conductive snaps [9, 11] to connect components to traces, users can remove them for maintenance and washability [7]. Additionally, weather-specific limitations, such as exposure to moisture, UV light, and extreme temperatures, pose challenges for integrating woven circuits into outdoor furniture and outerwear. Addressing these limitations will require further research into protective coatings, insulation methods, and weather-resistant materials to ensure that woven circuits maintain functionality in diverse conditions.

In Section 4, we conducted experiments on WovenCircuits' performance in terms of washability and shrinkage by measuring resistance and dimensions under lab-controlled conditions. However, we have not assessed its stretchability and durability under daily use, where extensive friction and flexing may impact performance. A more comprehensive "in-the-wild" evaluation may be required to fully understand the real-world performance of these woven circuits, particularly in long-term, high-use scenarios.

7.6 Restrictions of Weaving Curved Shapes

WovenCircuits can support the weaving of complex shapes, such as U-shaped traces (see Figure 7). By using tapestry needles at both ends of a single conductive thread and weaving from the middle of the thread until the point where the U-shape branches, we effectively preserve the continuity of the trace. However, WovenCircuits does not accommodate weaving inverted U-shaped traces that start from two branches and then join i.e. non-continuous shapes. These are shapes with two regions sharing the same weaving step but are separated by a gap across the weft. Similar to how shapes can branch out during the weaving process, as with U-shaped traces, two branches may also merge to form a single continuous region. For non-conductive areas, weavers can simply add an additional tapestry needle for each branch. However, in conductive regions, introducing a second conductive-threaded needle for each branch would result in discontinuities, compromising the electrical connection and potentially causing functional errors in the circuit. While we worked around this limitation in the ThirstyCat Tapestry by inverting the T2 draft in the "background" areas where the branches merge (see Figure 20), this solution has drawbacks. Because the draft is inverted, the conductive trace surfaces on the bottom layer of the fabric, leaving the trace uninsulated. As a result, this approach may not be suitable for wearable applications.

8 Conclusion

Weaving presents an opportunity for extended forms of hybrid crafts [1, 36, 52, 79, 87], allowing researchers and makers to seamlessly integrate functionality and aesthetics into everyday things in the home and on the body. Adopting an RtD [90] approach, we explored WovenCircuits to address this gap by investigating the underexplored area of connection traces and introducing fabrication techniques that enable insulating electrodes (T1), housing electrical components (T2), and weaving electrical connections (T3). This approach enables larger-scale, real-world applications, building on the knowledge on swatches [9, 29, 53], patches [8, 46], and bits [37, 38], and supporting more complex and functional e-textile designs.

Our work also provides a detailed exploration of key design factors influencing the performance of woven circuits, such as trace dimensions (F1), weaving structure (F2), and number of conductive thread strands (F3). Our experiments evaluated the conductivity of linear traces as well as areas for pad connections before and after several washes. Results show that resistance measurements remain relatively stable after the second laundering trial, with shrinkage levels exhibiting the expected behaviour of other regular woven cotton (i.e. 7% average vertical shrinkage for area traces across the three design factors and no horizontal shrinkage). Results also show that 3 strands and 'satin' weaving structure exhibits the best trade-off/balance between resistance and amount of conductive thread used for weaving linear and connection areas.

Through the set of fully functional research products, we demonstrate the diversity of applications that WovenCircuits can help create (wearables, objects on the go, on tables, chairs, floors, and walls). Finally, we offer a discussion on the design opportunities and limitations to guide future researchers and practitioners in creating complete and scalable woven circuits.

Acknowledgments

This project was funded by the National Sciences and Engineering Research Council of Canada (NSERC) through a Discovery Grant (2021-04135) and a Research Tools and Instruments (RTI) Grant (2021-00079), as well as through the Social Sciences and Humanities Research Council (SSHRC) NFRF-E-2024-01082. We acknowledge the support of Ontario Research Fund and the Canada Foundation for Innovation (CIF) for this research.

References

[1] Lea Albaugh, Jesse T Gonzalez, and Scott E Hudson. 2024. Tensions and Resolutions in Hybrid Basketry: Joining 3D Printing and Handweaving. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Cork, Ireland) *(TEI '24)*. Association for Computing Machinery, New York, NY, USA, Article 52, 13 pages. https://doi.org/10.1145/3623509.3633400

[2] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3290607.3313270

[3] Lea Albaugh, Scott E. Hudson, Lining Yao, and Laura Devendorf. 2020. Investigating Underdetermination Through Interactive Computational Handweaving. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. ACM, Eindhoven Netherlands, 1033–1046. https://doi.org/10.1145/3357236.3395538

[4] Charles K. Alexander and Matthew N. O. Sadiku. 2013. *Fundamentals of electric circuits* (5th ed ed.). McGraw-Hill, New York, NY.

[5] Ahmed Awad, Salma Ibrahim, and Sara Nabil. 2024. Integrating e-Threads: Properties of Conductive Threads for Electrical Connectivity Using Computational

Weaving of Smart Textiles. In *2024 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*. IEEE, Kingston, ON, Canada, 643–647.

[6] Madeline Balaam, Anna Ståhl, Guðrún Margrét Ívansdóttir, Hallbjörg Embla Sigtryggsdóttir, Kristina Höök, and Caroline Yan Zheng. 2024. Exploring the Somatic Possibilities of Shape Changing Car Seats. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference* (Copenhagen, Denmark) *(DIS '24)*. Association for Computing Machinery, New York, NY, USA, 3354–3371. https://doi.org/10.1145/3643834.3661518

[7] Mary Ellen Berglund, James Coughlin, Guido Gioberto, and Lucy E. Dunne. 2014. Washability of e-textile stretch sensors and sensor insulation. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers*. ACM, Seattle Washington, 127–128. https://doi.org/10.1145/2634317.2634326

[8] Amanda Boone, Eileen Rivera, and Jacob Wolf. 2018. Patchwork: an expressive e-textile construction kit. In *Proceedings of the 17th ACM Conference on Interaction Design and Children* (Trondheim, Norway) *(IDC '18)*. Association for Computing Machinery, New York, NY, USA, 529–532. https://doi.org/10.1145/3202185.3210770

[9] Leah Buechley and Michael Eisenberg. 2009. Fabric PCBs, electronic sequins, and socket buttons: Techniques for e-textile craft. *Personal and Ubiquitous Computing* 13, 2 (2009), 133–150. https://doi.org/10.1007/s00779-007-0181-0

[10] Alice Buso, Holly McQuillan, Milou Voorwinden, and Elvin Karana. 2023. Weaving Textile-form Interfaces: A Material-Driven Design Journey. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. ACM, Pittsburgh PA USA, 608–622. https://doi.org/10.1145/3563657.3596086

[11] Artem Dementyev, Tomás Vega Gálvez, and Alex Olwal. 2019. SensorSnaps: Integrating Wireless Sensor Nodes into Fabric Snap Fasteners for Textile Interfaces. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 17–28. https://doi.org/10.1145/3332165.3347913

[12] Laura Devendorf, Sasha De Koninck, and Etta Sandry. 2022. An Introduction to Weave Structure for HCI: A How-to and Reflection on Modes of Exchange. In *Designing Interactive Systems Conference*. ACM, Virtual Event Australia, 629–642. https://doi.org/10.1145/3532106.3534567

[13] Laura Devendorf and Chad Di Lauro. 2019. Adapting Double Weaving and Yarn Plying Techniques for Smart Textiles Applications. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 77–85. https://doi.org/10.1145/3294109.3295625

[14] Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M. Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. "I don't Want to Wear a Screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, San Jose California USA, 6028–6039. https://doi.org/10.1145/2858036.2858192

[15] Laura Devendorf and Daniela K. Rosner. 2017. Beyond Hybrids: Metaphors and Margins in Design. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (Edinburgh, United Kingdom) *(DIS '17)*. Association for Computing Machinery, New York, NY, USA, 995–1000. https://doi.org/10.1145/3064663.3064705

[16] Laura Devendorf, Kathryn Walters, Marianne Fairbanks, Etta Sandry, and Emma R Goodwill. 2023. AdaCAD: Parametric Design as a New Form of Notation for Complex Weaving. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 127, 18 pages. https://doi.org/10.1145/3544548.3581571

[17] Laura Devendorf, Shanel Wu, and Mikhaila Friske. 2023. Making Design Tools Like a Weaver: Four Rules. *XRDS: Crossroads, The ACM Magazine for Students* 29, 4 (June 2023), 54–58. https://doi.org/10.1145/3596929

[18] Dilara Egeli, Mine Seçkin, Ahmet Çağdaş Seçkin, and Eren Oner. 2022. Woven Fabric Produced From Coaxial Yarn for Touch Sensing and Optimization. *IEEE Sensors Journal* 22, 6 (2022), 5969–5977. https://doi.org/10.1109/JSEN.2022.3143904

[19] Ylva Fernaeus, Martin Jonsson, and Jakob Tholander. 2012. Revisiting the jacquard loom: threads of history and current patterns in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Austin Texas USA, 1593–1602. https://doi.org/10.1145/2207676.2208280

[20] Mikhaila Friske, Shanel Wu, and Laura Devendorf. 2019. AdaCAD: Crafting Software For Smart Textiles Design. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300575

[21] William Gaver and Andy Boucher. 2024. Designing with Data: An Annotated Portfolio. *ACM Trans. Comput.-Hum. Interact.* 31, 6, Article 71 (Dec. 2024), 25 pages. https://doi.org/10.1145/3685272

[22] Khosrow Golshan. 2007. *Physical design essentials: an ASIC design implementation perspective.* Springer, New York.

[23] Ramyah Gowrishankar. 2017. Constructing triboelectric textiles with weaving. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (Maui, Hawaii) *(ISWC '17)*. Association for Computing Machinery, New York, NY, USA, 170–171. https://doi.org/10.1145/3123021.3123037

[24] Sofía Guridi, Emmi Pouta, Ari Hokkanen, and Aayush Jaiswal. 2023. LIGHT TISSUE: Development of cellulose-based optical textile sensors. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction* (Warsaw, Poland) *(TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 27, 14 pages. https://doi.org/10.1145/3569009.3572798

[25] Brett A. Halperin, William Rhodes, Kai Leshne, Afroditi Psarra, and Daniela Rosner. 2024. Resistive Threads: Electronic Streetwear as Social Movement Material. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference* (Copenhagen, Denmark) *(DIS '24)*. Association for Computing Machinery, New York, NY, USA, 69–85. https://doi.org/10.1145/3643834.3661537

[26] Kaja Seraphina Elisa Hano and Valkyrie Savage. 2024. Hybrid Crochet: Exploring Integrating Digitally-Fabricated and Electronic Materials with Crochet. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Cork Ireland, 1–6. https://doi.org/10.1145/3623509.3635257

[27] Claire Harvey, Emily Holtzman, Joy Ko, Brooks Hagan, Rundong Wu, Steve Marschner, and David Kessler. 2019. Weaving objects: spatial design and functionality of 3D-woven textiles. In *ACM SIGGRAPH 2019 Art Gallery* (Los Angeles, California) *(SIGGRAPH '19)*. Association for Computing Machinery, New York, NY, USA, Article 5, 8 pages. https://doi.org/10.1145/3306211.3320137

[28] Shiqing He and Eytan Adar. 2020. Plotting with Thread: Fabricating Delicate Punch Needle Embroidery with X-Y Plotters. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1047–1057. https://doi.org/10.1145/3357236.3395540

[29] Anja Hertenberger, Barbro Scholz, Beam Contrechoc, Becky Stewart, Ebru Kurbak, Hannah Perner-Wilson, Irene Posch, Isabel Cabral, Jie Qi, Katharina Childs, Kristi Kuusk, Lynsey Calder, Marina Toeters, Marta Kisand, Martijn ten Bhömer, Maurin Donneaud, Meg Grant, Melissa Coleman, Mika Satomi, Mili Tharakan, Pauline Vierne, Sara Robertson, Sarah Taylor, and Troy Robert Nachtigall. 2014. 2013 e-textile swatchbook exchange: the importance of sharing physical work. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program* (Seattle, Washington) *(ISWC '14 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 77–81. https://doi.org/10.1145/2641248.2641276

[30] Kunpeng Huang, Md. Tahmidul Islam Molla, Kat Roberts, Pin-Sung Ku, Aditi Galada, and Cindy Hsin-Liu Kao. 2021. Delocalizing Strain in Interconnected Joints of On-Skin Interfaces. In *Proceedings of the 2021 ACM International Symposium on Wearable Computers* (Virtual, USA) *(ISWC '21)*. Association for Computing Machinery, New York, NY, USA, 91–96. https://doi.org/10.1145/3460421.3478812

[31] Kunpeng Huang, Ruojia Sun, Ximeng Zhang, Md. Tahmidul Islam Molla, Margaret Dunne, Francois Guimbretiere, and Cindy Hsin-Liu Kao. 2021. WovenProbe: Probing Possibilities for Weaving Fully-Integrated On-Skin Systems Deployable in the Field. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1143–1158. https://doi.org/10.1145/3461778.3462105

[32] E. Häntzsche, A. Matthes, A. Nocke, and Ch Cherif. 2013. Characteristics of carbon fiber based strain sensors for structural-health monitoring of textile-reinforced thermoplastic composites depending on the textile technological integration process. *Sensors and Actuators, A: Physical* 203 (2013), 189–203. https://doi.org/10.1016/j.sna.2013.08.045

[33] Salma Ibrahim and Sara Nabil. 2025. E-Serging: Exploring the Use of Overlockers (Sergers) in Creating E-Textile Seams and Interactive Yarns for Garment Making, Embroidery, and Weaving. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '25)*. Association for Computing Machinery, New York, NY, USA, Article 41, 17 pages. https://doi.org/10.1145/3689050.3704428

[34] Richard C. Jaeger. 2002. *Introduction to microelectronic fabrication* (2nd ed ed.). Number v. 5 in Modular series on solid state devices. Prentice Hall, Upper Saddle River, N.J.

[35] Lee Jones, Ahmed Awad, Marion Koelle, and Sara Nabil. 2024. Hand Spinning E-textile Yarns: Understanding the Craft Practices of Hand Spinners and Workshop Explorations with E-textile Fibers and Materials. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference* (Copenhagen, Denmark) *(DIS '24)*. Association for Computing Machinery, New York, NY, USA, 1–19. https://doi.org/10.1145/3643834.3660717

[36] Lee Jones and Sara Nabil. 2022. Goldwork Embroidery: Interviews with Practitioners on Working with Metal Threads and Opportunities for E-textile Hybrid Crafts. In *Proceedings of the 14th Conference on Creativity and Cognition* (Venice, Italy) *(C&C '22)*. Association for Computing Machinery, New York, NY, USA, 364–379. https://doi.org/10.1145/3527927.3532809

[37] Lee Jones, Sara Nabil, and Audrey Girouard. 2020. Swatch-bits: Prototyping E-textiles with Modular Swatches. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 893–897. https://doi.org/10.1145/3374920.3374971

[38] Lee Jones, Sara Nabil, Amanda McLeod, and Audrey Girouard. 2020. Wearable Bits: Scaffolding Creativity with a Prototyping Toolkit for Wearable E-textiles. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 165–177. https://doi.org/10.1145/3374920.3374954

[39] Lee Jones, Miriam Sturdee, Sara Nabil, and Audrey Girouard. 2021. Punch-Sketching E-textiles: Exploring Punch Needle as a Technique for Sustainable, Accessible, and Iterative Physical Prototyping with E-textiles. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 21, 12 pages. https://doi.org/10.1145/3430524.3440640

[40] Vanessa Kamara, Sahil K. Kargwal, Nick Constant, Renee Gordon, George Humphreys, and Kunal Mankodiya. 2019. A Comparative Characterization of Smart Textile Pressure Sensors. In *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, Berlin, Germany, 1745–1748. https://doi.org/10.1109/EMBC.2019.8856901

[41] Hsin-Liu Cindy Kao, Abdelkareem Bedri, and Kent Lyons. 2018. SkinWire: Fabricating a Self-Contained On-Skin PCB for the Hand. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 3, Article 116 (sep 2018), 23 pages. https://doi.org/10.1145/3264926

[42] Rohit Ashok Khot and Jung-Ying (Lois) Yi. 2020. GustaCine: Towards Designing a Gustatory Cinematic Experience. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 757–770. https://doi.org/10.1145/3374920.3375010

[43] Rohit Ashok Khot, Jung-Ying (Lois) Yi, and Deepti Aggarwal. 2020. SWAN: Designing a Companion Spoon for Mindful Eating. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 743–756. https://doi.org/10.1145/3374920.3375009

[44] Yuya Koyama, Michiko Nishiyama, and Kazuhiro Watanabe. 2018. Smart Textile with Plain Weave Structure Using Hetero-Core Optical Fiber Sensor and Wool Threads. In *2018 International Conference on Intelligent Autonomous Systems (ICoIAS)*. IEEE, Singapore, 18–22. https://doi.org/10.1109/ICoIAS.2018.8493642

[45] Christian Krauter, Katrin Angerbauer, Aimée Sousa Calepso, Alexander Achberger, Sven Mayer, and Michael Sedlmair. 2024. Sitting Posture Recognition and Feedback: A Literature Review. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 943, 20 pages. https://doi.org/10.1145/3613904.3642657

[46] Pin-Sung Ku, Kunpeng Huang, and Cindy Hsin-Liu Kao. 2022. Patch-O: Deformable Woven Patches for On-body Actuation. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 615, 12 pages. https://doi.org/10.1145/3491102.3517633

[47] Sabrina Lakhdhir, Charles Perin, and Sowmya Somanath. 2024. Expressive Clothing: Understanding Hobbyist-Sewers' Visions for Self-Expression Through Clothing. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 858, 17 pages. https://doi.org/10.1145/3613904.3642338

[48] Anne Lamers, Evy Murraij, Elze Schers, and Armando Rodríguez Pérez. 2019. Layered embroidery for dynamic aesthetics. In *Proceedings of the 2019 ACM International Symposium on Wearable Computers* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 302–305. https://doi.org/10.1145/3341163.3346942

[49] Eldy S. Lazaro Vasquez, Mirela Alistar, Laura Devendorf, and Michael L. Rivera. 2024. Desktop Biofibers Spinning: An Open-Source Machine for Exploring Biobased Fibers and Their Application Towards Sustainable Smart Textile Design. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 856, 18 pages. https://doi.org/10.1145/3613904.3642387

[50] Young Suk Lee. 2015. Spiky Starfish: Exploring 'Felt Technology' Through a Shape Changing Wearable Bag. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 419–420. https://doi.org/10.1145/2677199.2690878

[51] Ivo Locher and Gerhard Tröster. 2007. Fundamental building blocks for circuits on textiles. *IEEE Transactions on Advanced Packaging* 30, 3 (Aug. 2007), 541–550. https://doi.org/10.1109/TADVP.2007.898636

[52] Yiyue Luo, Kui Wu, Tomás Palacios, and Wojciech Matusik. 2021. KnitUI: Fabricating Interactive and Sensing Textiles with Machine Knitting. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 668, 12 pages. https://doi.org/10.1145/3411764.3445780

[53] Hua Ma and Junichi Yamaoka. 2022. SenSequins: Smart Textile Using 3D Printed Conductive Sequins. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 85, 13 pages. https://doi.org/10.1145/3526113.3545688

[54] Tom Martin, Mark Jones, Justin Chong, Meghan Quirk, Kara Baumann, and Leah Passauer. 2009. Design and Implementation of an Electronic Textile Jumpsuit. In *2009 International Symposium on Wearable Computers*. IEEE, Linz, Austria, 157–158. https://doi.org/10.1109/ISWC.2009.25

[55] Giorgio Mattana, Thomas Kinkeldei, David Leuenberger, Caglar Ataman, Jinyu J. Ruan, Francisco Molina-Lopez, Andrés Vásquez Quintero, Giovanni Nisato, Gerhard Tröster, Danick Briand, and Nico F. De Rooij. 2013. Woven temperature and humidity sensors on flexible plastic substrates for e-textile applications. *IEEE Sensors Journal* 13, 10 (2013), 3901–3909. https://doi.org/10.1109/JSEN.2013.2257167

[56] Ali Maziz, Alessandro Concas, Alexandre Khaldi, Jonas Stålhand, Nils-Krister Persson, and Edwin W. H. Jager. 2017. Knitting and weaving artificial muscles. *Science Advances* 3, 1 (Jan. 2017), e1600327. https://doi.org/10.1126/sciadv.1600327

[57] Jussi Mikkonen and Emmi Pouta. 2015. Weaving electronic circuit into two-layer fabric. In *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers* (Osaka, Japan) *(UbiComp/ISWC'15 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 245–248. https://doi.org/10.1145/2800835.2800936

[58] Jussi Mikkonen and Emmi Pouta. 2016. Flexible Wire-Component for Weaving Electronic Textiles. In *2016 IEEE 66th Electronic Components and Technology Conference (ECTC)*, Vol. 2016-August. Institute of Electrical and Electronics Engineers Inc., Las Vegas, NV, USA, 1656–1663. https://doi.org/10.1109/ECTC.2016.180

[59] Sara Mlakar and Michael Haller. 2020. Design Investigation of Embroidered Interactive Elements on Non-Wearable Textile Interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3313831.3376692

[60] Md. Tahmidul Islam Molla, Crystal Compton, and Lucy E. Dunne. 2018. Launderability of surface-insulated cut and sew E-textiles. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers* (Singapore, Singapore) *(ISWC '18)*. Association for Computing Machinery, New York, NY, USA, 104–111. https://doi.org/10.1145/3267242.3267255

[61] Sara Nabil, Aluna Everitt, Miriam Sturdee, Jason Alexander, Simon Bowen, Peter Wright, and David Kirk. 2018. ActuEating: Designing, Studying and Exploring Actuating Decorative Artefacts. In *Proceedings of the 2018 Designing Interactive Systems Conference* (Hong Kong, China) *(DIS '18)*. Association for Computing Machinery, New York, NY, USA, 327–339. https://doi.org/10.1145/3196709.3196761

[62] Sara Nabil, Lee Jones, and Audrey Girouard. 2021. Soft Speakers: Digital Embroidering of DIY Customizable Fabric Actuators. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Salzburg Austria, 1–12. https://doi.org/10.1145/3430524.3440630

[63] Sara Nabil and David Kirk. 2021. Decoraction: a Catalogue for Interactive Home Decor of the Nearest-Future. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 98, 13 pages. https://doi.org/10.1145/3430524.3446074

[64] Sara Nabil, David S. Kirk, Thomas Plötz, Julie Trueman, David Chatting, Dmitry Dereshev, and Patrick Olivier. 2017. Interioractive: Smart Materials in the Hands of Designers and Architects for Designing Interactive Interiors. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (Edinburgh, United Kingdom) *(DIS '17)*. Association for Computing Machinery, New York, NY, USA, 379–390. https://doi.org/10.1145/3064663.3064745

[65] Sara Nabil, Jan Kučera, Nikoletta Karastathi, David S. Kirk, and Peter Wright. 2019. Seamless Seams: Crafting Techniques for Embedding Fabrics with Interactive Actuation. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 987–999. https://doi.org/10.1145/3322276.3322369

[66] Digital Weaving Norway. 2024. TC2 Loom: Digital Weaving Machine. https://digitalweaving.no/tc2-loom/

[67] Momoko Okazaki, Ken Nakagaki, and Yasuaki Kakehi. 2014. metamoCrochet: augmenting crocheting with bi-stable color changing inks. In *ACM SIGGRAPH 2014 Posters* (Vancouver, Canada) *(SIGGRAPH '14)*. Association for Computing Machinery, New York, NY, USA, Article 19, 1 pages. https://doi.org/10.1145/2614217.2633391

[68] Daniëlle Ooms, Nick Voskuil, Kristina Andersen, and Hanna Ottilia Wallner. 2020. Ruta, a Loom for Making Sense of Industrial Weaving. In *Companion Publication of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS' 20 Companion)*. Association for Computing Machinery, New York, NY, USA, 337–340. https://doi.org/10.1145/3393914.3395815

[69] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and Michael Haller. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 745–756. https://doi.org/10.1145/3242587.3242664

[70] Jane Patrick. 2010. *The weaver's idea book: creative cloth on a rigid heddle loom.* Interweave Press, Loveland, CO. OCLC: 853448168.

[71] Irene Posch. 2021. Crafting Stories: Smart and Electronic Textile Craftsmanship for Interactive Books. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 100, 12 pages. https://doi.org/10.1145/3430524.3446076

[72] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 4216–4227. https://doi.org/10.1145/2858036.2858176

[73] Emmi Pouta and Jussi Ville Mikkonen. 2022. Woven eTextiles in HCI — a Literature Review. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 1099–1118. https://doi.org/10.1145/3532106.3533566

[74] Emmi Pouta, Jussi Ville Mikkonen, and Antti Salovaara. 2024. Opportunities with Multi-Layer Weave Structures in Woven E-Textile Design. *ACM Trans. Comput.-Hum. Interact.* 31, 5, Article 62 (Nov. 2024), 38 pages. https://doi.org/10.1145/3689039

[75] Thomas Preindl, Cedric Honnet, Andreas Pointner, Roland Aigner, Joseph A. Paradiso, and Michael Haller. 2020. Sonoflex: Embroidered Speakers Without Permanent Magnets. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 675–685. https://doi.org/10.1145/3379337.3415888

[76] Annamaria Recupero, Patrizia Marti, and Simone Guercio. 2021. Balancing guidance and flexibility in the design of an inclusive handweaving loom: Balancing guidance and flexibility. In *European Conference on Cognitive Ergonomics 2021*. ACM, Siena Italy, 1–4. https://doi.org/10.1145/3452853.3452892

[77] T. Scott Saponas, Chris Harrison, and Hrvoje Benko. 2011. PocketTouch: through-fabric capacitive touch input. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology* (Santa Barbara, California, USA) *(UIST '11)*. Association for Computing Machinery, New York, NY, USA, 303–308. https://doi.org/10.1145/2047196.2047235

[78] Ruojia Sun, Ryosuke Onose, Margaret Dunne, Andrea Ling, Amanda Denham, and Hsin-Liu (Cindy) Kao. 2020. Weaving a Second Skin: Exploring Opportunities for Crafting On-Skin Interfaces Through Weaving. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 365–377. https://doi.org/10.1145/3357236.3395548

[79] Ruojia Sun, Ryosuke Onose, Margaret Dunne, Andrea Ling, Amanda Denham, and Hsin-Liu (Cindy) Kao. 2020. Weaving a Second Skin: Exploring Opportunities for Crafting On-Skin Interfaces Through Weaving. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 365–377. https://doi.org/10.1145/3357236.3395548

[80] Yanan Wang, Hebo Gong, and Zhitong Cui. 2021. ScenThread: Weaving Smell into Textiles. In *Adjunct Proceedings of the 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 83–85. https://doi.org/10.1145/3474349.3480235

[81] Rundong Wu, Claire Harvey, Joy Xiaoji Zhang, Sean Kroszner, Brooks Hagan, and Steve Marschner. 2020. Automatic structure synthesis for 3D woven relief. *ACM Trans. Graph.* 39, 4, Article 102 (Aug. 2020), 10 pages. https://doi.org/10.1145/3386569.3392449

[82] Rundong Wu, Joy Xiaoji Zhang, Jonathan Leaf, Xinru Hua, Ante Qu, Claire Harvey, Emily Holtzman, Joy Ko, Brooks Hagan, Doug James, François Guimbretière, and Steve Marschner. 2020. Weavecraft: an interactive design and simulation tool for 3D weaving. *ACM Trans. Graph.* 39, 6, Article 210 (Nov. 2020), 16 pages. https://doi.org/10.1145/3414685.3417865

[83] Shanel Wu, Xavier A Corr, Xi Gao, Sasha De Koninck, Robin Bowers, and Laura Devendorf. 2024. Loom Pedals: Retooling Jacquard Weaving for Improvisational Design Workflows. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Cork, Ireland) *(TEI '24)*. Association for Computing Machinery, New York, NY, USA, Article 10, 16 pages. https://doi.org/10.1145/3623509.3633358

[84] Tony Wu, Shiho Fukuhara, Nicholas Gillian, Kishore Sundara-Rajan, and Ivan Poupyrev. 2020. ZebraSense: A Double-sided Textile Touch Sensor for Smart Clothing. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 662–674. https://doi.org/10.1145/3379337.3415886

[85] Tianhong Catherine Yu, Riku Arakawa, James McCann, and Mayank Goel. 2023. uKnit: A Position-Aware Reconfigurable Machine-Knitted Wearable for Gestural Interaction and Passive Sensing using Electrical Impedance Tomography. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 628, 17 pages. https://doi.org/10.1145/3544548.3580692

[86] Clint Zeagler, Scott Gilliland, Halley Profita, and Thad Starner. 2012. Textile Interfaces: Embroidered Jog-Wheel, Beaded Tilt Sensor, Twisted Pair Ribbon, and Sound Sequins. In *Proceedings of the 2012 16th Annual International Symposium on Wearable Computers (ISWC) (ISWC '12)*. IEEE Computer Society, USA, 60–63. https://doi.org/10.1109/ISWC.2012.29

[87] Clement Zheng, Bo Han, Xin Liu, Laura Devendorf, Hans Tan, and Ching Chiuan Yen. 2023. Crafting Interactive Circuits on Glazed Ceramic Ware. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 474, 18 pages. https://doi.org/10.1145/3544548.3580836

[88] Jingwen Zhu, Nadine El Nesr, Nola Rettenmaier, and Cindy Hsin-Liu Kao. 2023. SkinPaper: Exploring Opportunities for Woven Paper as a Wearable Material for On-Skin Interactions. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 479, 16 pages. https://doi.org/10.1145/3544548.3581034

[89] Jingwen Zhu, Lily Winagle, and Hsin-Liu (Cindy) Kao. 2024. EcoThreads: Prototyping Biodegradable E-textiles Through Thread-based Fabrication. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 857, 17 pages. https://doi.org/10.1145/3613904.3642718

[90] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through design as a method for interaction design research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '07)*. Association for Computing Machinery, New York, NY, USA, 493–502. https://doi.org/10.1145/1240624.1240704

[91] Christoph Zysset, Kunigunde Cherenack, Thomas Kinkeldei, and Gerhard Tröster. 2010. Weaving Integrated Circuits into Textiles. In *International Symposium on Wearable Computers (ISWC) 2010*. International Symposium on Wearable Computers (ISWC) 2010, Seoul, Korea (South), 1–8. https://doi.org/10.1109/ISWC.2010.5665874