E-Sewing: Exploring the Design Space of Machine-Sewing E-Textile Circuits

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ABSTRACT

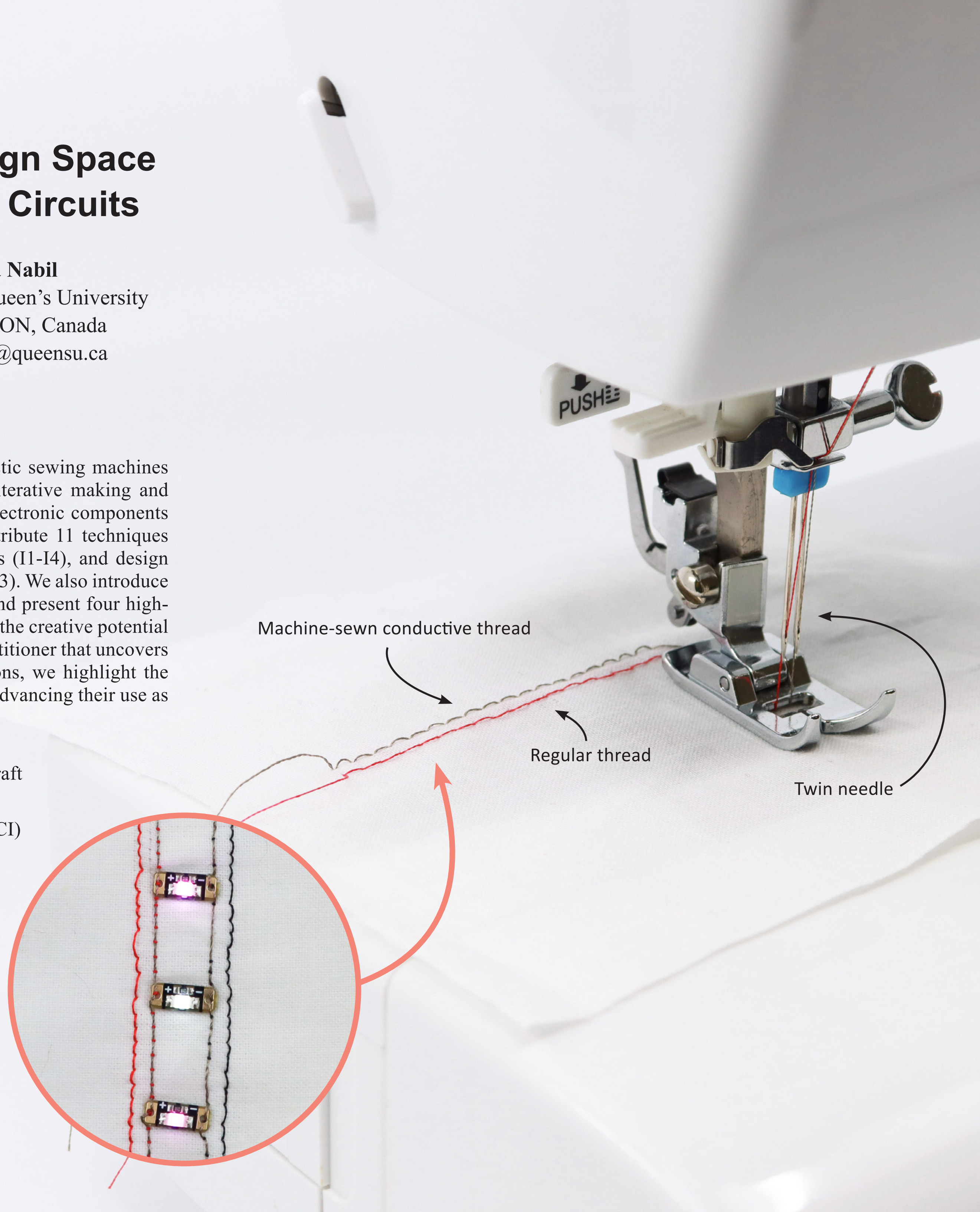
This pictorial presents a design research exploration of domestic sewing machines as hybrid craft tools for creating e-textile circuits. Through iterative making and experimentation, we examine how conductive materials and electronic components can be integrated into fabric using sewing machines. We contribute 11 techniques for securely terminating connections (T1-T4), insulating wires (I1-I4), and design possibilities for sewing LEDs and electronic components (A1-A3). We also introduce four types of machine-sewn sensors (S1-S4) for interactivity and present four high-fidelity prototypes of machine-sewn circuits. To further explore the creative potential of these techniques, we engaged in a case study with a craft practitioner that uncovers design insights and limitations. Reflecting on these explorations, we highlight the role of sewing machines in democratizing e-textile design and advancing their use as accessible tools for hybrid fabrication.

Authors Keywords

sewing; e-sewing; sewing machine; sensors; e-textile; hybrid craft

CSS Concepts

• Human-centered computing~Human computer interaction (HCI)



DIS '25, July 5–9, 2025, Funchal, Portugal

ACM ISBN 979-8-4007-1485-6/25/07…
https://doi.org/10.1145/3715336.3735416

INTRODUCTION

E-sewing has been defined as "the creation of circuits from sewable electronic components and conductive thread" [41]. As a hybrid craft, it is central to the broader domain of e-textiles. The increasing availability of conductive fabrics, fibres, and threads has democratized the design of textile-based interactive systems, offering opportunities for hybrid crafters to transform everyday objects and wearables into future interactive interfaces [34, 49, 50] as envisioned in Decoraction [51] and Interioraction [52]. E-textile research in HCI has explored a wide range of crafting techniques, including weaving [9, 11, 64, 66], knitting [2, 35, 43, 44, 67], crocheting [11, 18, 54], embroidery [27, 37, 39, 50, 69], patchwork [3], serging [25, 61], and punch-needling [22, 30]. Among these, hand-sewing [57] has been used in HCI research due to its accessibility and adaptability, making it ideal for beginners [28, 29] and as part of STEM education kits [7, 24, 41, 74].

Machine-sewing, on the other hand, has primarily been used as a supplementary fabrication tool for prototype development across various domains, such as augmenting clothing to track motion [15, 61, 68], creating shape-changing interactions [36, 46, 53], exploring the use of smart materials [13, 45, 55, 60], and enabling customization and self-expression [16, 19]. Despite its proven potential, focusing on sewing machines as a stand-alone tool for constructing e-textile circuits is still underexplored. Unlike embroidery machines and industrial sewing machines, which typically require more investment or digital design expertise, domestic sewing machines are more cost-effective and accessible, lowering the barrier to entry for beginners. This accessibility, combined with their ability to partially automate the stitching process, positions domestic sewing machines as an untapped resource for advancing e-textile fabrication and democratizing the design process for hobbyists, makers, and craft practitioners.

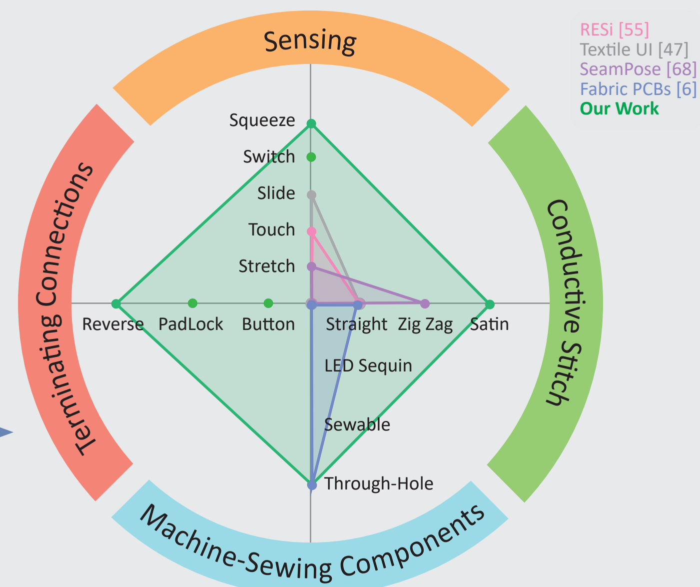
We were inspired to explore and investigate the tool itself – domestic sewing machines – by engaging in a Research through Design (RtD) [12] exploration of the broader design space of e-sewing and the practical challenges involved. We began our design research by aiming to develop a deeper understanding of machine-sewn conductive threads, creating an annotated portfolio [14] of stitch samplers that helped develop our collection of techniques. We explored these techniques for constructing machine-sewn e-textiles, which we validate by engaging in a case study with a craft practitioner. Using these techniques, we designed and created research products that helped us understand the design possibilities and expand the design space of sewing machines in HCI literature. Thus, this pictorial presents three key contributions, as follows.

- **An exploration of e-textile machine-sewing techniques** for sewing LEDs and electronic components (A1-A3); securely terminating connections (T1-T4), insulating wires (I1-I4); and creating machine-sewn sensors (S1-S4).
- **Applications demonstrating sensors, actuators, and interactive elements** integrated using our proposed techniques into four research products, in addition to guidelines for constructing machine-sewn e-textile circuits.
- **An exploratory case study with a sewing craft practitioner** to validate our techniques and their creative potential, reflecting on lessons learned from their personal craft practice.

RELATED WORK

Prior work [40] has recognized sewing as both a hybrid craft technique and a tool to support the development of physical prototypes, including wearable [16, 31, 36, 62, 68] and non-wearable [26, 36, 50, 53, 63] artefacts. While sewing conductive threads can be done entirely by hand [41], the automation and consistency offered by sewing machines has the advantages of building more robust and scalable e-textiles. Previous works have developed sewing and stitching techniques using smart materials to embed actuation and shape-changing capabilities [36, 53]. Recent work, SeamPose [68], aimed to improve activity recognition techniques by embedding machine-sewn conductive thread in clothing seams, creating an unintrusive method for movement data collection.

While hybrid craft research in other practices has focused on the sensing capabilities that can be achieved with integrating conductive materials in their practices, machine-sewing sensors remain underexplored. For example, work on interactive ceramicware [70] developed three kinds of sensors to understand their



affordances on a new medium. Sketch&Stitch [17] used conductive threads in digital embroidery machines to allow a craft practitioner to design three sensor-containing e-textile circuits. Sensing Kirigami [71] explored paper crafts and created two main sensor types to understand their resistive properties and behaviours. Inspired by this approach, we were motivated to create sensors solely using a domestic sewing machine.

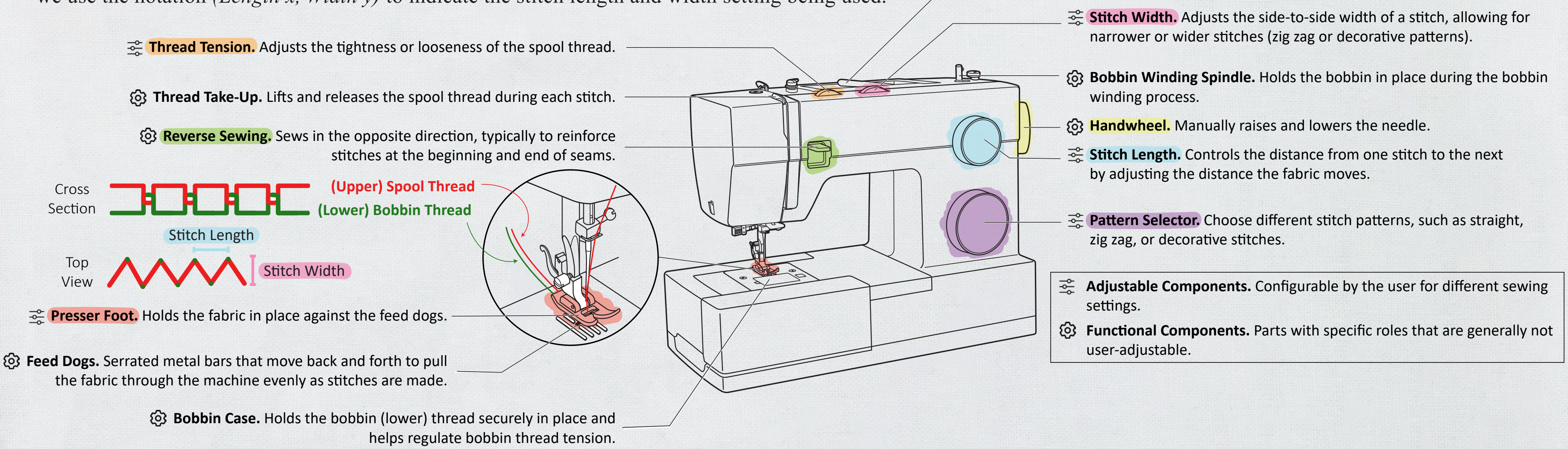
The DIY and maker communities have produced numerous books [8, 23, 33], tutorials [75-77] and kits [5, 7] for e-textile education, with a particular focus on beginners and students. These resources often introduce low-barrier circuits such as simple light-up LED projects. They typically rely on hand-sewing with conductive thread or the use of alligator clips, making it easier to illustrate basic circuit concepts and engage participants quickly. However, due to their introductory nature, these materials rarely delve into more complex, high-fidelity applications that go beyond elementary circuits. Consequently, the valuable knowledge gained is often not built upon to develop more robust and practical e-textile designs.

Recent work in HCI has explored ways to make e-textile fabrication more scalable and replicable without losing its craft-oriented qualities. Although we see circuits incorporating LED toolkits [59], socket buttons [6], sequin [45], and beads [69] for integrating switches and sensors, these techniques are still frequently hand-stitched or require expensive, steep learning curve embroidery machines. Furthermore, existing prototypes, such as for smart sleeves [56, 65] and smart shoes [20, 32, 72], often employ machine-sewing in limited roles, rather than showcasing it as a primary method for e-textile construction.

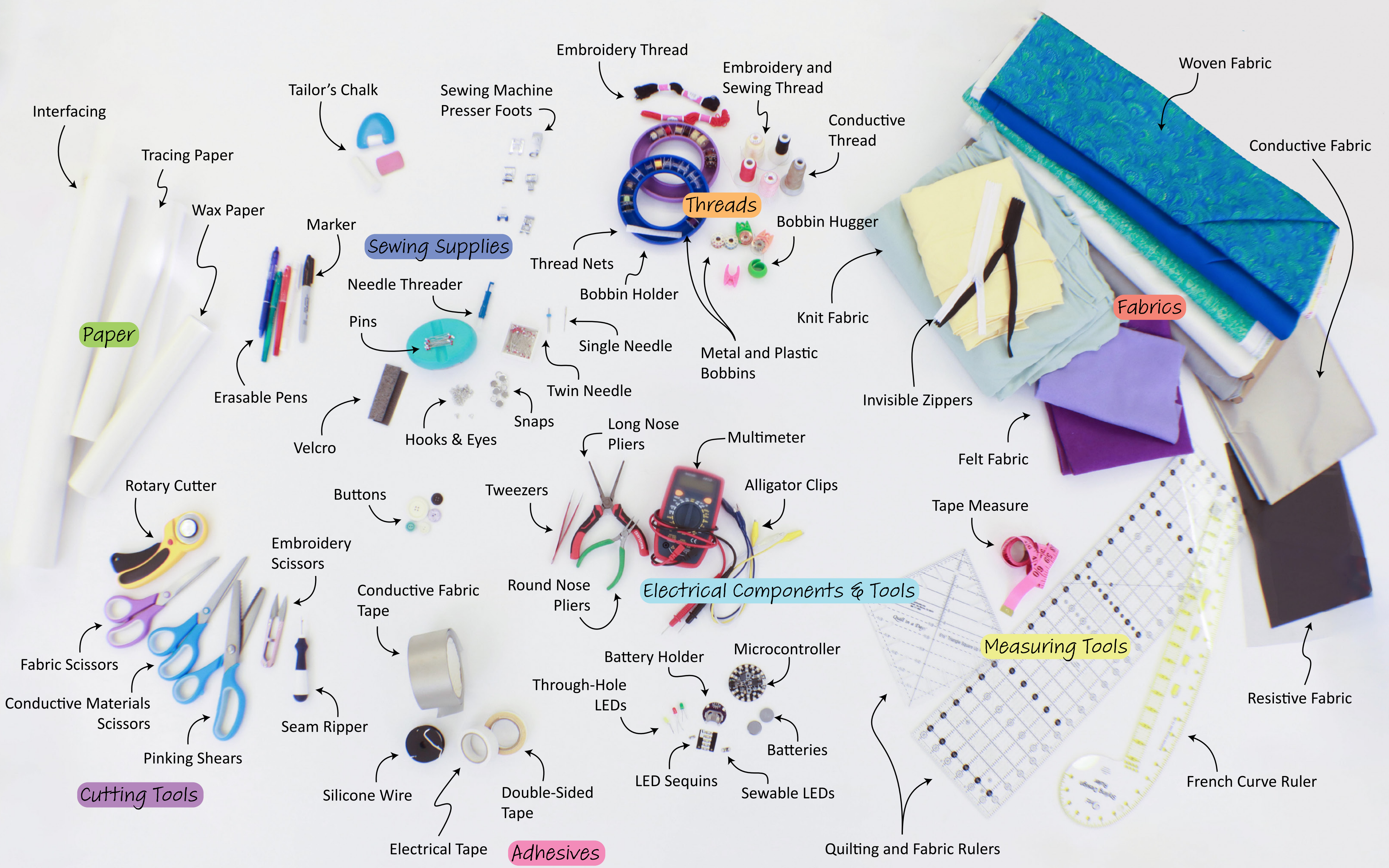
While these approaches demonstrate the growing interest in e-textiles for real-world applications, they focus on the application or material, rather than the practical method for using the tools themselves (i.e. sewing machines). For instance, work on machine-sewing with resistive yarns [55] recommends using the material as bobbin thread, while regular thread is used in the top spool. However, methods for securing and terminating those connections or insulating and sewing electric gauge wires are not mentioned. Other work discusses how "thread [can be] too large to be used a top thread in a sewing machine" [4], but this excludes all applications where electronic components can be machine-sewn since the conductive thread would not make contact with the components at the top of the fabric. Therefore, we are motivated to understand how conductive thread can be used in the top spool and explore opportunities for machine-sewing sewable, through-hole, and sequin LEDs and other electronic components entirely using a domestic sewing machine, limiting the hand-stitching required.

THE ANATOMY OF A SEWING MACHINE

Sewing machines are mechanical devices comprising various components that work in unison to produce stitches with precision. While many machines share fundamental parts and functions, there are variations in design and features across different models. Here, we highlight the most important machine features that are needed to help create machine-sewn e-textiles. In this pictorial, we use the notation *(Length x, Width y)* to indicate the stitch length and width setting being used.



Materials


Paper
Interfacing
Tracing Paper
Wax Paper
Sewing Supplies
Tailor's Chalk
Sewing Machine Presser Foots
Marker
Erasable Pens
Needle Threader
Pins
Single Needle
Twin Needle
Velcro
Hooks & Eyes
Snaps
Threads
Embroidery Thread
Embroidery and Sewing Thread
Conductive Thread
Bobbin Hugger
Thread Nets
Bobbin Holder
Metal and Plastic Bobbins
Fabrics
Woven Fabric
Conductive Fabric
Knit Fabric
Invisible Zippers
Felt Fabric
Resistive Fabric
Cutting Tools
Rotary Cutter
Embroidery Scissors
Fabric Scissors
Conductive Materials Scissors
Pinking Shears
Seam Ripper
Buttons
Adhesives
Conductive Fabric Tape
Silicone Wire
Electrical Tape
Double-Sided Tape
Electrical Components & Tools
Tweezers
Long Nose Pliers
Round Nose Pliers
Multimeter
Alligator Clips
Battery Holder
Microcontroller
Through-Hole LEDs
Batteries
LED Sequins
Sewable LEDs
Measuring Tools
Tape Measure
Quilting and Fabric Rulers
French Curve Ruler

RESISTANCE CHARACTERIZATION OF CONDUCTIVE STITCHES

Stitch width and length, along with the stitch type and base fabric, impact the structural and electrical properties of machine-sewn conductive thread. We explored the resistive characteristics of these combinations, providing guidelines for their optimal use.

Methodology

In our RtD, we machine-sewed over 15m of stitches, creating an annotated portfolio [10, 14, 21] of stitch samplers, iterations, and failed attempts, where techniques are discovered and discarded [1]. Experiments were replicated by two researchers on two domestic sewing machines: the Singer Tradition 2282 and the Singer Heavy Duty 4411. We used two types of fabric: woven (100% cotton) and knit (95% Tencel, 5% spandex)—which are commonly used amongst makers [38], providing a starting point for understanding resistive behaviour across fabric types. We experimented with five commercially available varieties of conductive thread and found that the Madeira HC-40 (100% Silver-plated, <300 Ω/m) was the most suitable for use in domestic sewing machines (top spool thread) as it is less prone to ripping or inconsistent stitching.

Three stitch types were evaluated: straight stitch, zig zag stitch, and satin stitch—each with varying stitch lengths, widths, or a combination of both. Resistance measurements, using a multimeter, were repeated 10 times for each stitch type and parameter variation. These averaged values were normalized (resistance per cm) for comparative analysis.

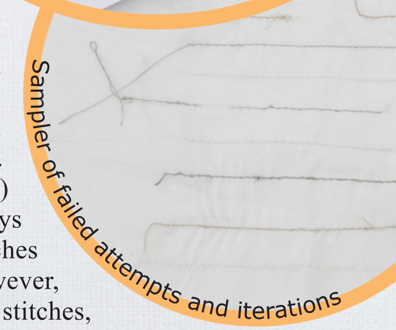
Findings

Woven Fabric. Straight stitches exhibited the lowest average resistance (12.9 Ω/cm) among all tested stitch types on woven fabric (24.9 Ω/cm for zig zag and 37.8 Ω/cm for satin), making them ideal for connections in soft circuits as they introduce minimal resistance, thus maximizing current flow to components. Resistance decreased consistently with longer stitches. A stitch length of 3 is an optimal compromise between low resistance (7.2 Ω/cm) and efficient material consumption. Zig zag stitches showed significantly higher average resistance (24.9 Ω/cm) compared to straight stitches, making them less suited for minimal-resistance applications. They may be more suitable as decorative conductive traces in designs where more resistance is tolerable.

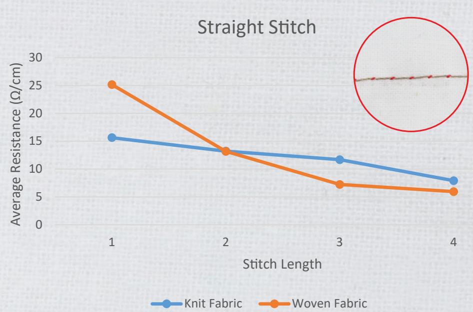
However, this makes them a great candidate for simulating fabric-based, or "soft", resistors. Satin stitches are zig zag stitches that are set to a length slightly above 0, which we called '0.1'. These stitches compress tightly, introducing contact resistance due to overlapping conductive threads. Although they demonstrated inconsistent and unpredictable resistance behaviour, we can take advantage of their high average resistance (37.8 Ω/cm) and compressed structure to substitute rigid resistor components in soft, fabric-based projects.

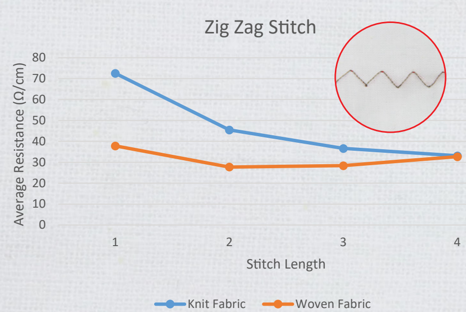
Knit Fabric. Like woven fabrics, straight stitches in knit fabric decreased with increasing stitch length, with a length of 3 being the optimal compromise between low resistance and material usage. The difference in average resistance for straight stitches between the two fabrics (12.1 Ω/cm for knits) can be considered negligible. Designers need not worry about the electrical considerations for straight stitches in knits and wovens but may make the decision on substrate based on material properties and aesthetics. In constrast, zig zag stitches showed a considerably lower average resistance on knits (12.1 Ω/cm) in comparison to their woven counterparts. This value (nearly half the resistance of woven fabric) suggests that they are more effective for resistive pathways in stretchy circuits. Furthermore, zig zag and straight stitches can be used for connections interchangeably on knits. However, zig zag stitches offer more slack in comparison to straight stitches, making them more suitable for flexible applications and stretch sensors.

Satin stitches can be applied as soft resistors on knit fabrics. Their average resistance (72.5 Ω/cm) significantly exceeded values on woven substrates. This can be attributed to the tighter fabric compression, which disrupts current flow more severely in elastic knit structures. Although this high value can be advantageous in creating a high-resistance soft resistor on a much smaller surface area, satin stitches can be cumbersome to control on knit fabrics. Often, the feed dogs may not move the fabric correctly due to the elasticity of the fabric, causing stitches to accumulate in one place. This can be resolved if the sewing machine is equipped with a differential feed adjustment, which would move knits more easily.



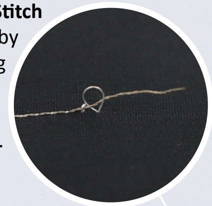
Sampler of failed attempts and iterations

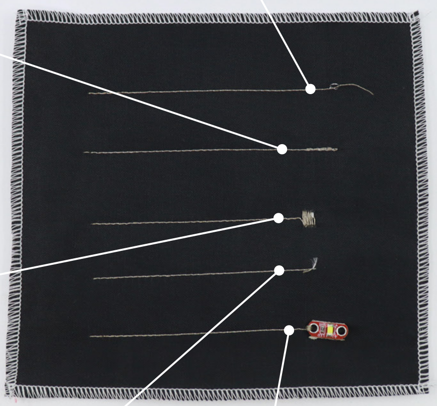




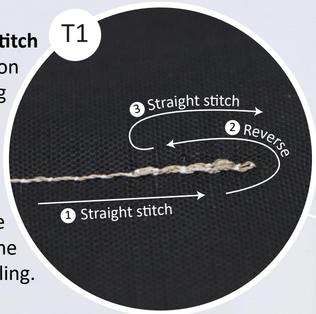
How to Securely Terminate Connections

Unsecured Stitch
When conductive thread connections are terminated simply by cutting after sewing, the end of the thread can loosen, leading to fraying and unreliable electrical connections. Based on our design explorations, we propose four techniques for proper termination, crucial to maintaining functionality and durability.

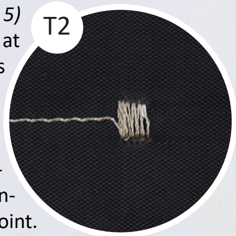




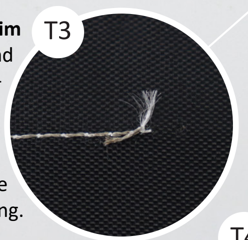
Reverse Lock Stitch
Reverse stitching, common amongst machine-sewing practitioners, at the end of a conductive straight stitch reinforces the connection by sewing over the same spot multiple times, preventing the thread from unravelling.



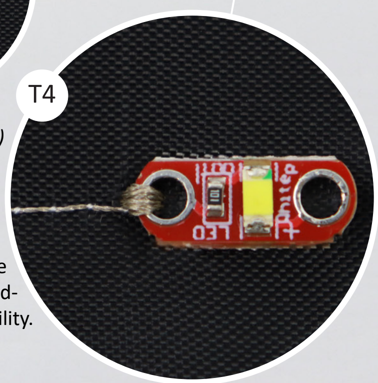
Pad Lock *(Length 0.1, Width 5)*
Switching to a wide zig zag stitch at the end of a straight stitch creates a dense and durable termination point (inspired by digital embroidery), securely holding the thread in place and allowing future components (or metal snaps) to be connected at that point.



Knot and Trim
By tying the thread ends together and trimming the excess, this method provides a simple and effective way to prevent fraying. Adding a drop of glue or clear nail polish (inspired by e-textile practitioners [23]) can further secure the knot from unraveling.

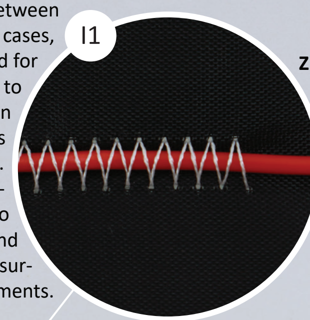


Connect to Component *(Length 0, Width 2)*
Similar to machine-sewing buttons, sewable components can be machine-sewn right after a connection line. Using a tight zig zag stitch (with the feed dogs lowered), the component can be secured to the fabric by precisely aligning the needle with the sewing-holes and stitching in place. The excess thread can be knotted at the back of the fabric for additional stability.

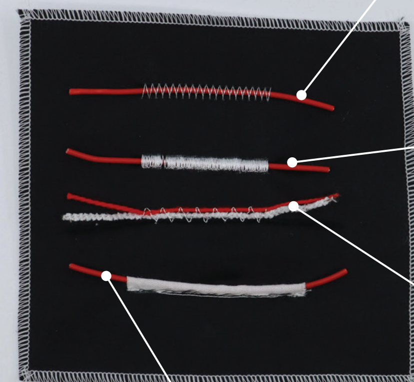


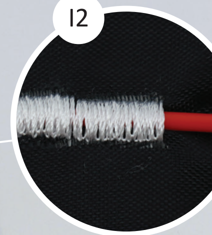
How to Insulate Wires

Researchers and e-textile practitioners often need to use electric wires to secure connections between sewable components [62]. In these cases, silicone and metallic wires can be used for their malleability and machine-sewn to secure them onto fabric. In our design research, we found four techniques appropriate for machine-sewing wires. Although silicone wires are already insulated, we can use these methods to further insulate them from wear and tear, protecting them from their surrounding environments.

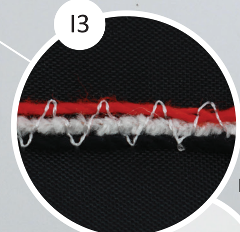


Zig Zag *(Length 2, Width 5)*
Use a zig zag stitch to couch wires securely onto fabric. This method works best for insulated or silicone wires, providing stability while leaving the wire accessible for connections.

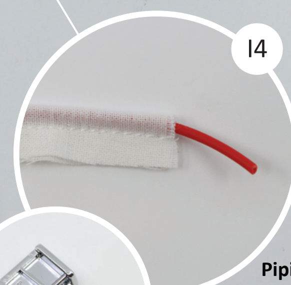


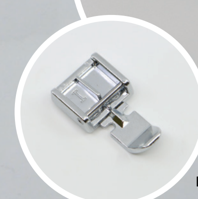


Satin Stitch *(Length 0.1, Width 5)*
A dense zig zag stitch fully encases the wire, offering both stability and insulation. Ideal for exposed, metallic wires or uninsulated conductive threads, this method can reduce the risk of accidental electrical shorts.



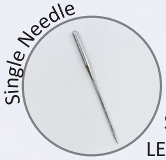
Cording *(Length 1, Width 5)*
The cording foot and a 3-point zig zag stitch are perfect for securing thicker conductive threads, like Karl-Grim solderable thread or chenille stems. This technique can also be decorative, with coloured yarns to visually differentiate power (red) and ground (black) as is common in electronics practice.





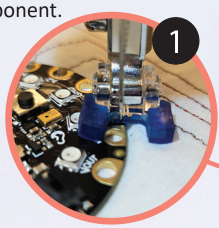
Piping
Insulate wires by encasing them in fabric using a piping or zipper foot. This method provides a clean and durable covering, ideal for protecting wires while maintaining a sleek design in wearables and interactive everyday things.

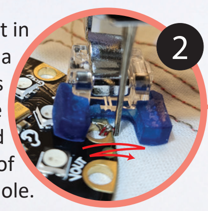
How to Machine-Sew LEDs and Components



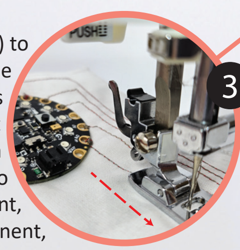
Method A1
Sewable Components Using Single Needles

Sewable components (such as microcontrollers, LEDs, and sensors) can be machine-sewn with the sewing machine set up with a single needle (conductive thread in the spool, regular thread in the bobbin) and a button presser foot. Select the zig zag stitch (length 0, width 2) and place the component between the fabric and the button foot. Align the needle of the machine to the hole of the sewable component.



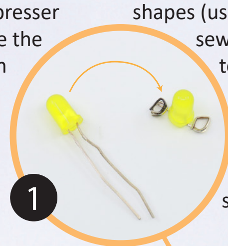


Begin stitching the component in place as you would sew a button. For added caution, this can be done by turning the handwheel to manually and repeatedly stitch in and out of the hole.

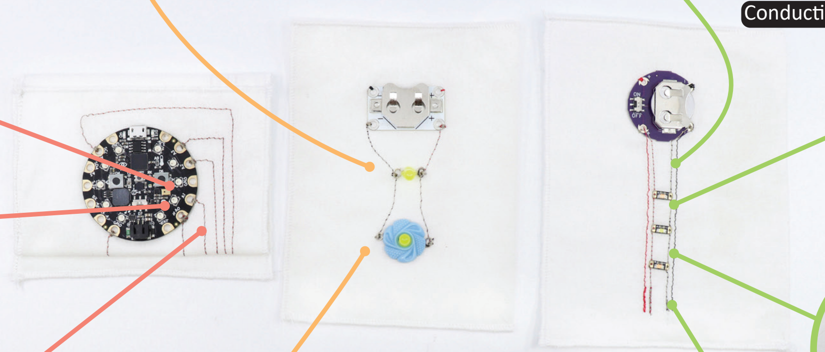


Switch to a straight stitch (length 4) to begin the connection from the component towards other components (e.g. LEDs). Once another component placement is reached, switch back to a zig zag stitch (length 0, width 2) to secure it in place. For each component, repeat steps 2-3 until the final component, where the connection will be terminated.

Method A2
Through-Hole Components Using Single Needles

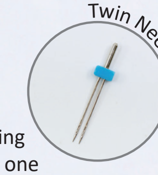


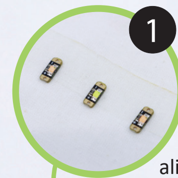
Through-hole LEDs and other electronic components, such as resistors and photosensors with leads, can be twisted into sewable round shapes (using pliers) to be easily and securely sewn onto fabrics using the same technique as Method A1. The long leads can also be easily secured using a satin stitch (I2); however, this technique (A2) offers more stability and prevents the component from slipping.



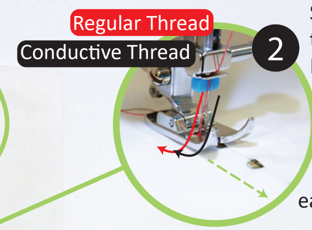
Buttons and other sew-throughs, such as beads and perforated ornaments, can be used to add through-hole electronic components in a more decorative fashion, making them blend less obtrusively and more seamlessly into garments.

Method A3
LED Sequins Using Twin Needles

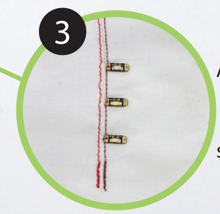




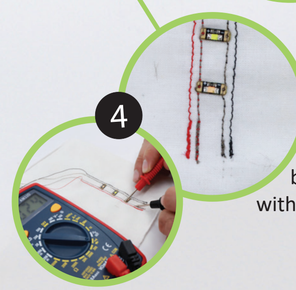
LED sequins in parallel can be sewn with the machine using a twin needle loaded with conductive thread in one needle (closest to the LED connection pad) and regular thread in the other. This method provides the advantage of color-coding conductive threads (e.g. red thread for the power side and black thread for the ground side). Begin by deciding and sketching (with a fabric erasable marker) where the LED sequins will be placed and aligning their +/- sides together.



Start sewing with a straight stitch on the power end of the LEDs (length 4) by precisely aligning the conductive thread needle with the sewing holes and stitching in place. Users can make use of the machine's handwheel when passing through each LED hole for better control.



After the last LED is machine-sewn in place, terminate that stitched connection (e.g. using T1 reverse lock stitch).



Repeat the previous steps for stitching the other side (e.g. the ground side), remembering to switch the placement of the threads in the needles (i.e. conductive in the left needle and black thread in the right). Check the connections with a multimeter.

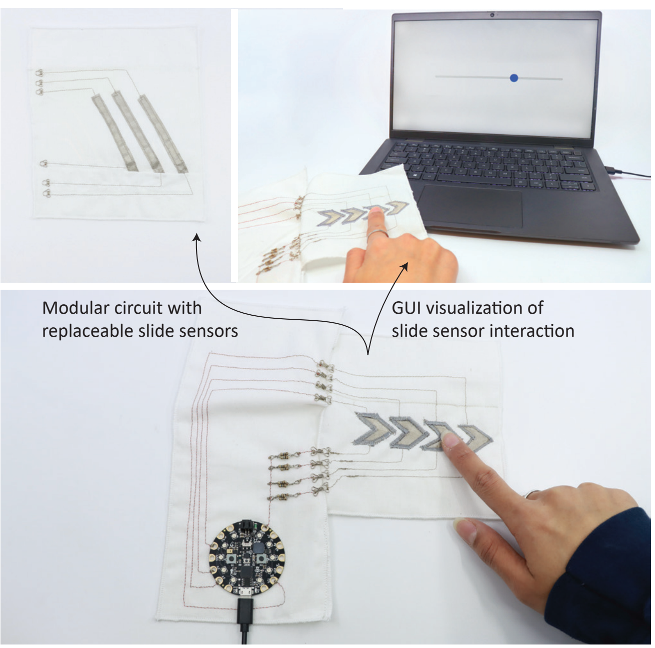
Pro Tip: Before sewing, place the components in the desired position (similar to aligning the needle with buttonholes), securing them onto the fabric with double-sided tape. For additional security and to protect components from any damage, cover one side at a time with tape, leaving the connection points exposed.

Machine-Sewn Sensors & Interactivity

Touch and Slide Sensor (S1)

Capacitive touch sensors can be machine-sewn by securing pieces of conductive fabric where desired, either as an individual touch point or a series of points that can collectively form a slide sensor. We experimented with different shapes for slide sensors, from basic geometric primitives (rectangles) and directional indicators (pointing arrows) to linear elements (parallel straight lines). Herein, we show one of our slide sensors that leverages the principle of movement direction [47] to communicate affordance, with arrow-shaped pieces of conductive fabric indicating the sliding direction.

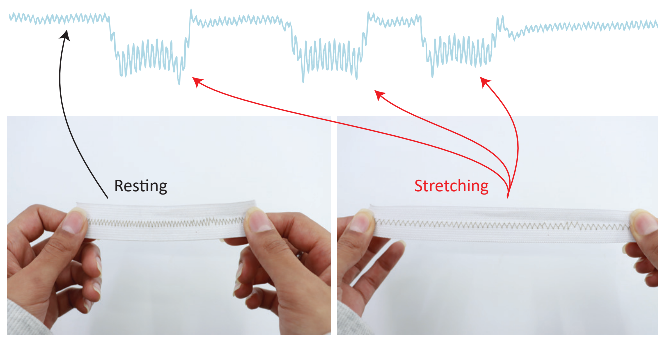
We cut the conductive fabric and stitched their perimeters onto a base fabric using conductive thread, connecting each isolated shape to an eyelet at the fabric's edge on either side, providing two connection points per shape. To prevent fraying, we added a protective satin stitch around the arrow perimeters using regular thread. On a separate fabric, we stitched the microcontroller with designated pins linked to hooks at the edge. Resistors can be added as an optional grounding mechanism and connected to the ground pin of the microcontroller. This modular approach enables the separation of the electronic components from the sensor for customization, washing, and debugging.

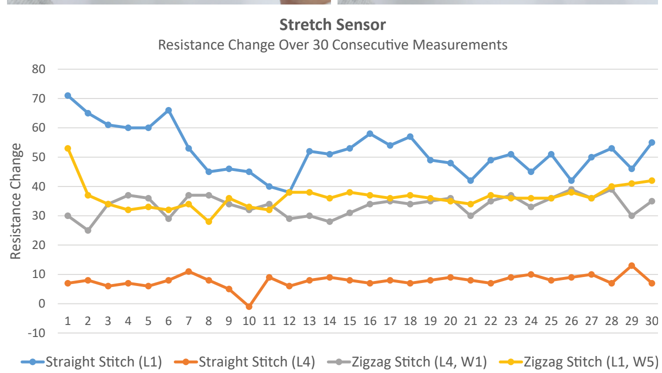


Stretch Sensor (S2)

To determine the most suitable stitches for stretch sensors, we conducted resistance tests on an elastic base. We evaluated the **stretchability** (the extent to which the elastic could stretch without significant hindrance from the stitch, measured using a ruler) and **resistance change** (the difference in resistance between the resting and stretched states, measured using a multimeter). A highly sensitive stretch sensor with more elasticity is advantageous for microcontroller detection. We used this sensor as a variable resistor in a voltage divider circuit using the Adafruit Circuit Playground Express and a 1K Ω resistor.

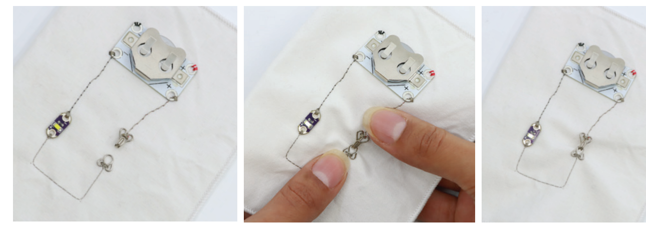
Among the different stitch configurations tested, a straight stitch (length 1) achieved the highest resistance sensitivity (4.4 Ω/cm), making it ideal for applications requiring precise detection of small changes in stretch. However, a zig zag stitch (length 1, width 5) offered the highest stretch (68%, compared to 24% on average for other stitches) with a 3.0 Ω/cm change. Therefore, we recommend short and wide zig zag stitches due to their combination of high stretchability and sensitivity to changes in resistance.





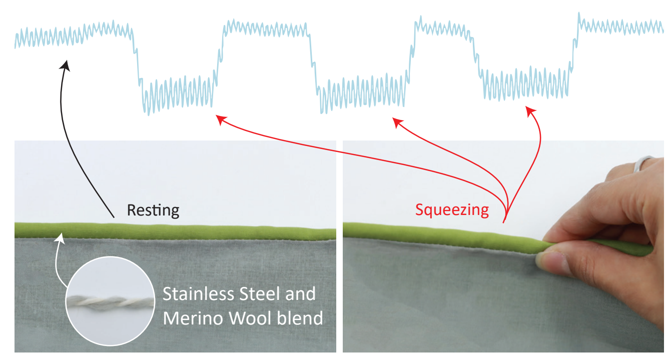
Switch Sensor (S3)

Traditional sewing practices incorporate materials like hooks and eyes, Velcro, snap fasteners, and zippers as opening and closing mechanisms, which can be repurposed as e-textile switches when crafted from conductive materials [6]. Conductive Velcro and metal snaps or hooks and eyes can serve as electric components, functioning as a switch sensor by forming a circuit that opens and closes based on physical contact. This approach is versatile and can be adapted with snaps or other conductive fasteners. During our design exploration, we often resorted to using such components to establish machine-sewn connections that can be switched on and off easily and seamlessly without requiring an additional obtrusive switch component.



Squeeze Sensor (S4)

Piping is used to insert decorative trim into seams by encasing a cord or filler material within a strip of fabric, which is then sewn into the seam. Building on this principle, we developed a squeeze sensor. We stitched a line of conductive thread on two fabric layers: the base fabric and the piping strip. The strip was filled with a blend of conductive fibres and stitched onto the base fabric using a piping foot. When the piping is squeezed, the conductive fibres make contact with the base conductive thread, causing a measurable change in resistance.



Applications of Machine-Sewn Sensors

BloomTracker Denim

E-Sewing Techniques: T4, I2, A1, S3, S4.

As a practical application fabric, we identified denim to be durable and sturdy for holding wearable components. We designed BloomTracker, a denim jacket with a machine-sewn GPS sensor for children during outdoor activities. The decorative, but functional, design on the back features a flower-in-pot and bird, created using a darning presser foot. The flower's petals attach via Velcro, allowing them to be removed and reveal a FLORA microcontroller hidden beneath. The bird's eye houses a GPS module connected to the FLORA (A1), enabling real-time location tracking. One of the petals, filled with conductive fibres, is a squeeze sensor (S4) that interacts with the FLORA through conductive Velcro (S3). To keep the design sleek and practical, the battery is discreetly hidden inside the flowerpot with the wires satin stitched (I2) to the fabric. The jacket blends creativity, safety, and wearable tech into one stylish garment.

GlowCourt Tee

E-Sewing Techniques: T3, I1, A2.

We designed a customized T-shirt for a volunteer's tennis club holiday party, aptly named the GlowCourt Tee. The original design showcased guinea pigs dressed in festive attire. We transformed this to incorporate tennis elements by embroidering tennis rackets and a ball soaring overhead. To elevate the design by incorporating interactive elements, we added illumination. In the background of the design, behind the front fabric, we attached white LEDs that are machine-sewn using A2 to create an array of stars in the sky behind the guinea pigs. A pocket sewn onto the side of the shirt holds a battery pack with a switch, allowing the wearer to control the lights easily. The wires of the battery pack are held securely to the shirt using zig zag insulation stitches (I1).

SlideSense Cardigan

E-Sewing Techniques: S1, I4, T2, T4, A1.

To experiment with the augmentation of sensors, we designed the SlideSense Cardigan with a machine-sewn slide sensor (S1) embedded in the sleeve cuff. Made with conductive fabric and sewn with conductive thread, the sensor connects to a microcontroller (T4), enabling gesture-based controls. The discreet placement ensures it blends seamlessly into the cardigan's design without compromising style. The slide sensor has potential applications such as adjusting music volume, scrolling through presentation slides, or controlling smartphone interactions with a simple swipe.

HeatSwitch Sweater

E-Sewing Techniques: T3, T4, I1, S3.

HeatSwitch combines comfort and practicality with a built-in, removable heating system in the back of the sweater. We used our machine-sewing techniques to create the e-textile circuit, featuring a hook-and-eye closure (S3), which functions as a switch. When the jacket is fastened, a natural interaction of indicating coldness, the connection activates the heating. Conductive thread runs through the lapel to connect the closures to snap fasteners on the inside (T3, T4). The circuit can be detached easily via the snaps for launderability. The circuit includes a microcontroller, electric heating pads, a LiPo battery, and a transistor. The circuit wires are securely held in place using zig zag insulation stitches (I1) that vary in width to accommodate different wire thicknesses. Potential applications can range from users who simply run cold or need extra warmth to those with medical conditions, such as arthritis, who may benefit from machine-sewing their targeted heating, in non-intrusive and seamless ways, into their favourite garment.

Tips & Tricks

Based on insights derived from our RtD approach for designing and constructing e-textile circuits, we present some practical tips to address common challenges encountered while prototyping machine-sewn e-textiles.

1 Making Temporary Connections

Before permanently stitching circuits onto fabric, it is crucial to test and verify circuit configurations. Common methods, such as using alligator clips, can be cumbersome, particularly when working with small sewable components (such as LED sequin) [58]. We propose two techniques to allow for quick and reliable testing before committing to permanent stitching, saving time and reducing potential errors in the design process.

a) **Safety pins for temporary connections.** Secure the component onto the fabric using a safety pin. Then attach the alligator clip to the safety pin. This method provides a larger, more stable surface for the alligator clip to grip.

b) **Staplers as temporary anchors.** Components can be stapled directly to the fabric. Alligator clips can be attached to the staples, which serve as sturdy contact points. Once testing is complete, the staples can be easily removed using a staple remover.

2 Measuring Resistance While Sewing

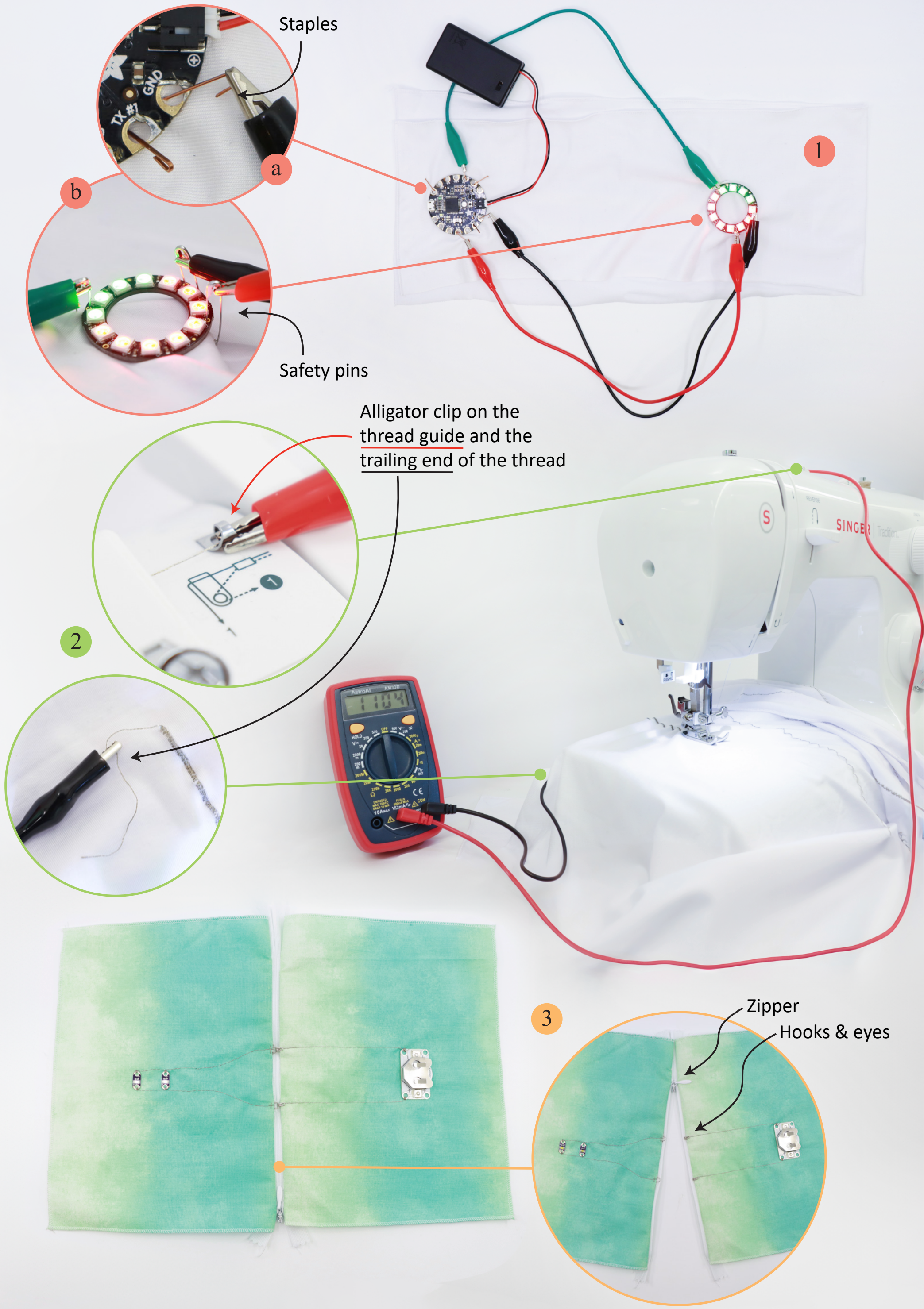
In applications requiring resistive elements, we can use soft resistors (satin stitches). By measuring resistance concurrently while sewing, designers can achieve more accurate results in real time. This technique is particularly beneficial for creating resistive elements with specific target values.

Connect a multimeter to the conductive thread as it is being sewn. One alligator clip is attached to the thread guide (at the point where the thread passes through), ensuring that the conductive thread still passes through smoothly while also making contact with the clip. The other clip is attached to the tail end of the conductive thread. The other side of both alligator clips are attached to the test probes of a multimeter. As the sewing progresses, the multimeter displays the resistance value, allowing designers to monitor changes and stop sewing once the desired resistance is reached.

3 Modular Circuits for Flexibility and Maintenance

Prototyping e-textile circuits often demands modularity to accommodate launderability, debugging, and iterative design. Detachable circuits can be implemented using various connection mechanisms, such as zippers, snaps, hooks & eyes, and conductive Velcro, to enhance the reusability and maintainability of prototypes.

Invisible zippers can be used to create discrete, separable sections within the prototype, while snaps, hooks & eyes, and Velcro provide a simple yet effective way to create detachable connections (such as in the HeatSwitch Sweater and Bloom Tracker Denim).



Craft Practitioner Case Study

To explore how traditional sewing might intersect with our e-sewing techniques, we conducted a case study of hands-on making and co-creation with a sewing practitioner, referred to here as "Hana" (Female, Homemaker, 47).

Study Procedure. Our study took place over a single session lasting three hours, followed by a 30-minute semi-structured interview. The session began with an introduction to e-textiles through the e-textile stitch sampler [29], followed by an exploration of our e-sewing materials, techniques, and sensor/actuator samples. Hana was then invited to brainstorm potential applications and create a prototype using these techniques and materials. Throughout the session, observations were recorded through photographs, hand-written notes, and later, an audio-recorded interview. This study was approved by our institutional research ethics board.

Collaboration and Co-Creation. We approached this case study as a collaborative design engagement, treating Hana as a co-creator. She was particularly fascinated by the machine-sewn sensors and discussed their potential applications. *"This would be especially useful for the elderly. If you can't get up or move, you can reach out just by touching."* She also quickly connected the techniques with her own needs and context. One idea that emerged was the "e-Apron," a functional and playful e-sewn garment inspired by her frustration with missing phone calls while cooking. Her apron design incorporated cotton fabric, ribbon ties, a microfiber cloth pocket, and featured a touch-sensitive phone-shaped icon on the chest (S1) connected to a modular circuit (hidden in the pocket) via conductive zig zag stitches. This would allow her to dry her hands swiftly and answer the phone with a quick touch, a creative and personally relevant use case that highlights how e-sewing can address everyday needs.

Material Reflections. Hana's familiarity with fabric properties – how they drape, stretch, and wear over time – proved invaluable in evaluating our techniques. She gave feedback on everything from working with fabrics to conductive materials: "*I am shocked at how much this conductive thread feels the same as regular thread, but it would be interesting to see how it behaves with different fabrics. I'd be worried about puckering if the fabric is too lightweight.*" Hana even pointed out the fraying that occurs when cutting our conductive fabric, noting that insulating the edges would be essential for working with this material. She also highlighted questions about washability and maintenance, admiring the techniques that support creating modular circuits: "*I feel like these components would be damaged in the washing machine [...] – it's really smart to be able to use zippers to separate [circuits] from the [garment].*" This concern aligns with known challenges around launderability [48], where a modular approach to e-textile circuits can help improve their longevity when hand-washing with mild detergent.

Tensions Between Tradition and Technology. Hana highlighted that a craft like machine-sewing carries aspects of memorability and invites moments of self-connection through the act of making. She reflected on how sewing reminded her of her late mother, who taught her the craft and would encourage her to build her own wardrobe, rather than purchasing ready-made clothing. "*Ready-made clothes were too expensive for our family. To wear something proper or presentable, we [...] made it for ourselves.*" Hana's deeply personal connection with her craft was evident even in her ideation process, where she aimed to take advantage of the possibilities of e-sewing to aid and assist her in daily activities, even brainstorming assistive wearables for her elderly father. Reflecting on potentially incorporating e-sewing in future projects, Hana emphasized that the merging of these practices should be done with the intention of "*serving [a function] and helping*". Whether the application serves as a tool for self-expression or aiding in daily activities, Hana believes that diverting from traditional making practices should be done meaningfully.

This case study offered a glimpse into how sewing practitioners might engage with machine-sewn e-textiles, highlighting the importance of subtlety, aesthetics, durability, and comfort. Hana emphasized the value of preserving the beauty of handmade items, while also harnessing the potential to support new experiences. Though the insights are drawn from a single perspective, they reflect potential entry points for broader engagement with the sewing community – particularly in exploring how makers might shape, adopt, or resist e-sewing.

Discussion

Through the Needle's Eye

Through our exploration of e-sewing, we aimed to expand the design space for sewing as a hybrid craft using domestic sewing machines. The techniques we developed address challenges in e-textile construction, such as ensuring reliable connections and building modular circuits for improved durability and adaptability of wearable garments. Previous work in HCI primarily used sewing machines as supplementary tools within larger fabrication workflows [16, 19, 63]. Our work positions these machines as stand-alone tools for designing and constructing e-textile circuits from start to finish. This approach defines a novel design space for domestic sewing machines as integral tools in e-textile fabrication. By focusing solely on machine-sewn techniques, we uncover new possibilities for crafting high-fidelity, functional artifacts without relying on additional tools such as embroidery machines or other digital fabrication technologies, which tend to be more costly for DIY-ers and makers.

Rather than treating sewing machines as ancillary, our contribution emphasizes their potential to streamline processes and democratize access to e-textile creation. Sewing machines, with their wide availability and affordability, offer unique advantages for both prototyping and producing scalable e-textile designs. Our work demonstrates that even with standard equipment and minimal additional resources, creators can achieve sophisticated designs, thus broadening participation in the field.

The collaboration with our sewing craft practitioner showed how existing knowledge of textile properties influences the adoption of new techniques. Traditional sewists often prioritize fabric behaviour, durability, and aesthetics. Machine-sewn e-textile techniques must therefore align with these values to be widely adopted. For instance, the use of zig zag insulation stitches (I1-I4) and modular circuits offers practical ways to preserve functionality without compromising the fabric's form.

Knots, Limitations, and Future Work

Tensions in Material Compatibility. Conductive thread electrical behaviour varies based on the thread used, fabric type, and machine settings, such as wider zig zag stitches on lightweight fabrics which can cause fabric puckering. Future work can expand testing across diverse materials, which would further strengthen our understanding of how to optimize performance and appearance for more complex machine-sewn circuits. Soft resistors are limited to low resistance because larger resistances require longer satin stitches. For example, a 100 Ω soft resistor consumes 2.65 cm of woven fabric, whereas 1K Ω would consume 26.5 cm, which is not practical. Thus, soft resistors are not compatible for circuits with large resistance requirements, such as in the HeatSwitch Jacket.

Tailoring Solutions with Tooling and Workarounds. While sewing machines provide consistency and repeatability, they also limit the nuanced control present in hand-sewing, the most prevalent hybrid craft used for e-textile education and toolkits [26, 29, 41], especially for delicate tasks like component placement and flexible circuit designs. We worked around these issues through our techniques by using soft resistors in place of rigid components and double-sided tape to secure small components to fabric before sewing. Furthermore, our research community can explore designing custom presser feet or attachments for sewing machines that would enable easier handling of electronic components and LEDs.

Sewing New Perspectives from Practitioners. While prior studies explored co-creation with e-textile crafters [29, 42, 73], they primarily focused on hand-sewing or embroidery. In contrast, our work investigates the use of the domestic sewing machine as a primary fabrication tool – an accessible and familiar device that enables techniques not easily achieved by hand, such as consistent zig zag stitches and soft resistors. The insights from our case study revealed how valuable direct engagement and co-creation with end-users can be in terms of their expertise, perspective, and ideas. Hana's thoughtful feedback provided a better understanding of the importance of meaningful integration of interactivity in handmade creations. Expanding this approach by involving a broader range of practitioners in a larger workshop study would allow for a more comprehensive evaluation and validation of the approach of this work. Such engagement could reveal further practical insights and novel applications, ensuring the accessibility and relevance of e-sewing across diverse user groups.

Conclusion

This work presents sewing machines as versatile tools for e-textile design. We explored their potential by experimenting with conductive materials and the resistive capabilities afforded by using different substrates and machine settings. Our results of resistance characterization of machine-sewn conductive threads show that straight connection stitches are best made with a length of 3 and satin stitches can be used as soft resistors, with different behaviour for woven and knit fabrics. Informed by this deeper understanding of their electrical behaviour, we identified and outlined 11 e-sewing techniques for fabricating machine-sewn circuits and four examples of machine-sewn sensors, offering researchers and makers a broader design space for e-sewing. We applied these approaches in four high-fidelity prototypes and an exploratory case study with a sewing practitioner who designed and created another prototype customized to their needs, validating and reflecting on our techniques. Through this process, we demonstrated how machine-sewing can be expanded, beyond conventional use, to create interactive and personalized fabric-based circuits.

Acknowledgements

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 a Queen's University Research Initiation Grant (RIG). We acknowledge the support of Ontario Research Fund and the Canada Foundation for Innovation (CIF) for this research.

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