Scaling E-Textile Production: Understanding the Challenges of Soft Wearable Production for Individual Creators

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ABSTRACT

Electronic textiles (e-textiles) incorporate functional capabilities into fabric forms, providing direct body contact not afforded by traditional hardware. While widely researched by the Wearable Computing community, e-textiles have yet to reach broad prevalence in the consumer market. A major obstacle lies in its scalable production. Specifically, moving from prototype to production remains elusive for individual researchers, makers, and startups. To better understand these challenges and pinpoint opportunities to reduce barriers, we conducted semi-structured interviews with 7 subject matter experts with experience in low volume production of e-textile products. We identified common challenges encountered during the prototype-to-production process and summarized our findings in four themes: (1) lack of production standards; (2) gaps between apparel and hardware manufacturing; (3) gaps in manufacturing costs vs. market expectations; and (4) lack of production-capable e-textile solutions. Our study revealed opportunities for future research on tools, materials, and community support specific to low-volume e-textile production. We envision that accessible low-volume e-textile production could enable more creators to bring their creations to the next step.

CCS CONCEPTS

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

KEYWORDS

E-textiles; wearable technology; low-volume manufacturing

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1 INTRODUCTION

E-textiles incorporate input sensing [13, 34, 40, 42, 47, 50, 51, 57, 65] and output actuation [26, 36, 39] into fabric forms, providing direct body contact not afforded by traditional hardware. While the Wearable Computing community has examined a broad range of applications and fabrication techniques, e-textiles have yet to reach broad prevalence in the consumer market. A major obstacle is the challenge in achieving mass production. Indeed, e-textile fabrication combines apparel and hardware manufacturing processes, integrating soft goods (slim soft circuitry) and hard goods (printed circuit boards and electronics). While both industries have well-established standards and protocols, scaling them remains a challenge [18, 29, 43].

There has been extensive research on improving the manufacturability of e-textiles, including the attachment of surface-mount components to e-textiles, blending conductive fiber to textiles, and improving the durability of interconnects [31, 41, 45, 60, 63]. They are, however, mostly designed for improving existing Cut-Make-Trim apparel factory facilities, and not to enable individual creators to move their prototypes to production.

Moreover, the lack of a standardized approach to the manufacture of soft circuitry with integrated hardware makes it difficult to scale up production to low volumes (i.e., less than 5000 units). Initiatives such as Project Jacquard [56], which is backed by Alphabet, Inc., have demonstrated the possibility of mass-producing smart textiles; however, individual researchers, makers and early-stage startups lack access to production resources on the same scale [35].

In order to better understand current soft wearable production challenges for individual creators, we conducted semi-structured interviews with subject matter experts with first-hand experience in low-volume soft circuitry production. The aim is to develop a more comprehensive and real-world picture and to identify opportunities to reduce barriers and ease the prototype-to-product transition for the unique category of soft circuitry production. We summarized our findings in the following themes:

(1) As a new commercial electronics category, e-textiles lack standard guidelines for production. As a result, creators (e-textile builders) often are left to their own devices to identify a path forward.
(2) There are gaps in apparel manufacturing and hardware manufacturing processes and timelines, leaving creators with the added responsibility to triage these gaps to realize e-textile production.
(3) These gaps also lead to e-textiles having higher manufacturing costs than expected by the market.
(4) Production-capable e-textile solutions are not widely accessible to individual creators, increasing the barrier of prototype-to-production transition.

2 BACKGROUND AND RELATED WORK

In this paper, we focus on soft wearable products that meet the following criteria:

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- It is designed to be worn on the body, which eliminates smart home device coverings or automotive interiors.
- It contains both soft and hard components. Various interconnections are used to electrically and mechanically connect the soft conductive or resistive materials to the hardware components. Products without circuitry (such as EMF shielding) are excluded, as they may not reflect hardware-textile integration challenges.
- It has been through low volume production. In our study, we define quantity lower than 5000 a year as low volume [35].

2.1 Prototyping E-Textiles: Electronic Toolkits and Fabrication Processes

Current approaches for rapidly prototyping e-textiles include the use of (1) toolkits, and also (2) novel fabrication approaches.

Toolkits: E-textile toolkits such as Lilypad [11, 12] and Flora [1] provide a series of microcontrollers, sensors, and actuators that can be integrated into fabrics [54]. The sewable pads are specifically designed to adapt to different soft circuitry materials such as conductive threads or conductive fabrics. Due to the accessibility of components and materials and the open-source community shared tutorials [5, 61], these tools are widely used in STEM education [12] and proof-of-concept prototypes for fashion technology designs.

However, in contrast to the widely available tutorials on how to make singular pieces for prototyping purposes, less public information is available for scaling the fabrication process from one to multiple. Even though companies like Alphabet, Inc. have demonstrated the capabilities of producing e-textile products in large quantities [56], the bridging step between prototype and low volume production remains unclear to the general public.

Fabrication Approaches: Beyond toolkits, fabrication approaches aim to integrate hard goods directly into soft interfaces. Fabrication processes include *surface level integration* of interactive elements through stitching [12, 46, 53], embroidery [2, 22–24, 27, 28, 48, 55, 65], felting [7, 33], silk-screening [37], and inkjet printing [64]. Weaving [8, 15–17, 19] and knitting [3, 25, 49, 62] afford *structural-level integration* of interactive elements at the yarn-level. However, these fabrication approaches are often labor-intensive and time-consuming. And because they involve handcrafting techniques and require certain knowledge in circuitry to create functioning circuits, there's no straightforward way to scale this to factory production.

Our study aims to reveal the obstacles in the prototype-to-low-volume production process for creators who aim to scale their e-textile projects beyond prototypes.

2.2 Strategies for E-Textile Mass Manufacture

Moving "beyond a prototype" has been a major challenge for hardware-based research in HCI [29, 30, 35]. While processes to move from prototype to low-volume manufacture have been investigated for hardware and mechanical systems, less efforts have been devoted to prototypes that involve soft circuitry [18, 21, 38, 43]. This is unsurprising, since soft circuitry systems incorporate the challenges of rigid hardware for integrated PCBs for "smart" capabilities, along with the unpredictable behaviors of soft form factors (e.g., fabrics) [18], posing a multi-faceted challenge.

Specifically, interconnection and hardware-textile integration remain a major challenge for e-textile production. Research has examined various interconnection designs to improve e-textile durability [31, 32, 59, 63] and stretchability [60], as well as surface-mount assembly on textiles [6, 44, 45].

However, these approaches are typically demonstrated in lab settings and by researchers with expertise in electronics and textiles. There is limited real-world deployment on how manufacturers adapt to these manufacturing techniques. Therefore, standard guidelines for hardware-textile integration and evaluation remain lacking. This knowledge is also not widely shared among maker communities in accessible formats such as easy-to-follow tutorials [5, 61]. Our study aims to identify these knowledge gaps and reveal opportunities to lower the barriers to e-textile production.

3 METHODS

Participants: We recruited 7 subject matter experts (all female) through snowball sampling, as shown in Table 1. Each participant had extensive experience creating e-textile products, and all have brought multiple soft wearable projects from prototype to production. All projects discussed align with the criteria defined in the Related Work section. Each participant received a gratuity of a $60 gift card.

ID	Role	Project Discussed	Quantity
1	Founder	Sound Activated Jackets	1000
2	Design Lead	Activity Sensing Pants	1000s
3	Tech Lead	Heating Garments	100
4	Design Lead	E-Textile Consultancy	50 - 1000
5	R&D Lead	Interface Jackets	1000s
6	Founder	Sweat Sensing T-Shirts	2000
7	Researcher	Performance Costumes	30

Table 1: Participants' IDs, roles, projects discussed and manufacture quantity of the discussed project.

Semi-Structured Interview Protocol: The semi-structured interviews were conducted over a 75-min Zoom session and recorded with permission. The audio transcripts were transcribed in Otter.ai and qualitatively coded by the authors via thematic analysis [10].

Each interview began with the participant's introduction of one representative project, the team makeup, and the goal for production. Participants then created their timeline from ideation to production. During the interview, we focused on the fabrication process, manufacturer partnership, sourcing, testing, and certification. We also asked them about tools, software, and cost.

4 FINDINGS

4.1 Theme 1: Lack of Production Standards

While e-textiles have been investigated in academic and industrial research for decades, it remains a new category of commercial electronics that lacks standards in the following aspects:

Process: Through timeline mapping during the interviews, we identified that e-textile production is a non-linear process. While most timelines consist of the product development phases of ideation, design, prototyping, engineering, testing, sourcing, and production, each critical step could initiate at vastly different time points. Of the 7 participants, 2 (P4, P5) did not complete the timeline mapping as they did not think it applies to their process. As P4 described: *"These things are really much more overlapping and stacked [...] this process is so dependent on many different factors."* In Figure 1, we summarized this variance with examples from three participants. This differs from the linear sequence observed in hardware production [35], which progresses clearly from phase 1 (ideation, experimentation, and design iteration) to phase 2 (verification tests and production). Participants attributed this to unsolved technical issues emerging throughout the process, such as challenges in iterative sourcing batteries to tradeoff capacity and size (P2, P3) and interconnection sourcing and testing (P2).

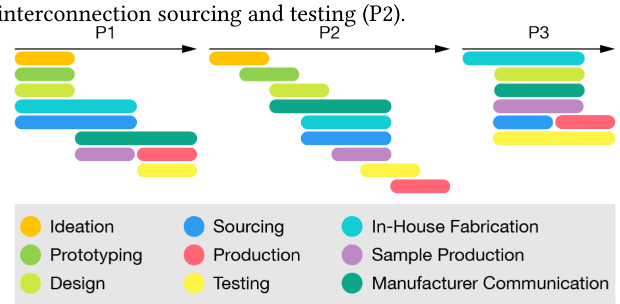

Figure 1: Production timeline mapping examples from P1, P2, and P3. We observe that unlike the liner timelines of hardware production, e-textile timelines are often nonlinear and overlapped.

Sourcing: The need for uncommon materials requires starting sourcing early (P1, P4, P5, P7). The uncommon materials include special trims for integrating electronics into textiles, conductive fibers, and fabrics. Custom orders are usually required due to the limited variety or quantity of off-the-shelf materials (P1, P7). For startups with limited resources, custom components can significantly raise the bill of materials cost.

Production: Without standard techniques for integrating soft circuitry components into textiles, fibers, and garments, creators must develop their own methods (P3). Solid manufacturer partnerships are essential for factories to adjust their production setups. In some cases, creators set up identical or equivalent production lines in-house. It ensures that prototyping changes are replicable in production and accelerates sampling for rapid iterations (P2, P3).

Testing: The lack of industry standards for testing obliged creators to devise their own testing plans and apparatus (P2, P3, P5). To reduce repetitive testing, P3 developed specialized fabrication methods that were extensively tested and reused across numerous client projects.

Software: E-textile design lacks software standards for file transfer and communication. Therefore, creators cater to what manufacturers have available to communicate specific requirements. For example, P2 and P3 create tech specs based on garment production file formats, incorporating additional information regarding the hardware. However, some technical details are still not precise in the files. Therefore, it becomes necessary to communicate in person. The creators stressed the importance of visiting factories to ensure manufacturers understand specific techniques (P2, P3, P4, P7).

Certification and Liability: E-textiles fall outside existing categories for certification, liability insurance, customs, and shipping (P3, P5). P3 mentioned that *"because it's an entirely new type of product, they didn't know how to categorize it or what to test for."* Moreover, lab testing does not necessarily reflect real-world conditions. P5 noted the battery issue in e-textiles for consumers: *"The battery can explode in the dryer. You can't assume that everyone would do a low-temperature cycle."*

4.2 Theme 2: Gaps between Apparel and Hardware Manufacturers

The e-textile industry lacks dedicated manufacturers that provide niche production services. Typically, creators work with apparel manufacturers and hardware manufacturers, and they must triage communications between these diverse parties (P1, P2, P3, P6).

Timeline: Separating apparel and hardware manufacturing often results in two timelines. The pace of development for apparel manufacturers tends to be faster than that for hardware manufacturers. Testing and debugging are essential when e-textiles are made with new fabrication techniques and production is iterative. Apparel manufacturers should be prepared for pattern changes and multiple iterations on a slower timeline. Progress slows when apparel production cannot change patterns to accommodate hardware engineering improvements (P3).

Knowledge: The knowledge and training required for both industries are also a challenge. Unlike researchers and creators, apparel manufacturers may lack the knowledge and experience to work with hardware. In response to these issues, P2 mentioned that their manufacturer partner hired an engineering team on their end to assist. Trivial mistakes could occur without hardware knowledge, such as sewing through an electronic component (P3).

Engineering Cost: The creators (P1, P3, P4, P6) who provide e-textile solutions as technical services also face challenges when working with fashion product clients. Hardware engineering costs could be unexpected for fashion clients unfamiliar with the hardware development process. Hardware manufacturers charge non-recurring engineering (NRE) fees to investigate the design and set up the production process [30, 35]. This one-time fee may be a high upfront cost that fashion clients did not anticipate (P3). Moreover, changes in sizing could result in rerouting circuit layout in hardware manufacturing, further increasing NRE fees (P3, P5).

4.3 Theme 3: Gaps in Manufacturing Costs vs. Market Expectations

Limited by current market size, the production quantity of the projects we interviewed is low: 30-2000, which is lower than the average production quantity for hardware or fashion products. *"2000 is a very low volume. (Most manufacturers) have minimums of 5000"* (P6). As a result, each wearable product would have a high manufacturing cost per item.

Furthermore, fashion products are valued differently from consumer electronics (P2, P5). Consumers will likely pay more for fashion items due to design, brand, and resale value. For creators, balancing production cost and margin is challenging due to the difference in expectations of unit price. Another factor contributing to the value gap was the product life difference. P5 pointed out that: *"[...] for electronics maybe they plan for five years,[...] but you could wear a jacket for 30 years. [...] When do we stop supporting our product?"*

4.4 Theme 4: Inaccessible Production-Capable E-Textile Solutions

Maker-centric and handcraft-based e-textile prototyping tools and fabrication processes are widely shared online [61], but few solutions can be directly transitioned for production. For example, online e-textile tutorials commonly use soldering and hand-stitching conductive thread techniques to connect hardware electronics and fabric materials. However, P7 pointed out that these techniques cannot be translated to factory machine operation. In contrast, manufacturing-level interconnect solutions have been examined in an academic context [31, 45, 58, 60, 63] but have yet to be distilled into online tutorials that are accessible to individual creators. The inaccessibility of resources for seamless prototype-to-production transition creates a high barrier for individual creators. P4 also commented that *"The interconnect, how you make it washable and how you connect all the other parts to it, is really hard"*. To cope with it, creators have to spend time and resources on sourcing and testing components and materials for production (P1, P2, P3, P6, P7). It results in increased unit cost as mentioned in section 4.3.

Consequently, due to the inaccessibility of production-ready materials and resources, e-textile expertise is often based on anecdotal experience since there are few instructions or tutorials to follow. Moreover, creators usually come from interdisciplinary backgrounds with rich experience in electronic hardware engineering and apparel design (P1-P7). E-textile production is therefore tricky for outsiders as entry-level designers or technologists.

5 OPPORTUNITIES

Reflecting on the interview findings, we distill the following opportunities for improving low-volume e-textile production (Figure 2).

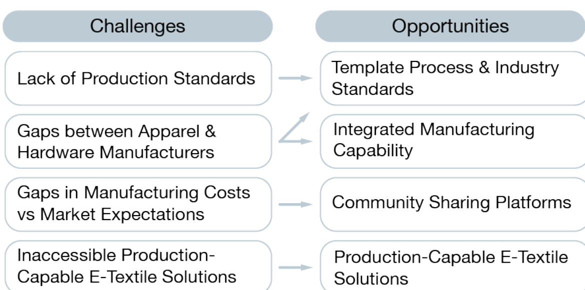

Figure 2: Mapping of "Challenges" to "Opportunities for Improvement" in e-textile production.

Process Templates and Industry Standards: There is a strong need for standardized processes in e-textile production. In the same way that P3 standardizes their fabrication methods through targeted testing (Section 4.1), there is potential to significantly reduce the time spent on engineering and development by using methods that have been thoroughly tested and certified [9, 14, 20, 43].

Software to communicate hardware-textile integrated products could reduce the dependence on in-person communication. Standard software could establish clear communication between textile and hardware manufacturers for overall product integration. P6 pointed out that: *"It may translate not just the software, but the language, the terminology, and the vocabulary."* P1 stated: *"It was important for our sample factory to see what we are looking for as a final outcome"*. We see the opportunity for more software tools such as AdaCAD [19] enabling creators to generate design files that integrate textile design and circuitry layout.

Community-Sharing Platforms: Early-stage creators can benefit from community-sharing platforms by learning from experienced creators. It could also complement existing e-textile education content that emphasizes handcrafting and DIY [12, 52]. For example, the Open Hardware Trailblazer Fellowships encourage individuals to document and share their experience making open source hardware in academia [4]. These programs provide incentives for individuals to publicly document and share their progress. *"I find that there are fewer resources [. . .] there are tons of people who have this experience.[. . .] So it will be great if there is more [documentation]"* (P7). Shared platforms among researchers and manufacturers could help establish this information exchange.

Integrated Manufacturing Capability: The disparity between hardware and apparel production creates technical and communication challenges. This gap indicates the need for a manufacturer with the ability to synthesize production needs from both domains. By producing with mature production techniques, creators could reduce tries and errors and lower upfront production costs. Moreover, an open-source pool of vendors and manufacturers could help creators find potential partners with matching production scales. P6 stated that *"it's hard to find someone who had the ability to take on low-volume [production], but also had expertise in complex assemblies of regular garments"*.

Production-Capable E-Textile Solutions: As shown in Figure 3, the lack of accessible corresponding tools for the production stage of e-textiles has increased the barrier for individual creators. We see an opportunity to create modular e-textile systems that are manufacturable and easy to prototype. Developing production-ready e-textile prototyping solutions could benefit individual creators and introduce industry standards. For example, P7 expressed the need for ubiquitously adaptable physical connectors that can be used in prototyping and also manufactured: *"I think we see different methods emerging, but they're not ubiquitous, and they're not readily accessible"*.

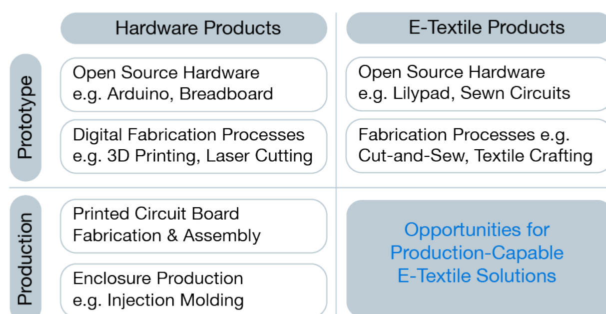

Figure 3: Comparing hardware and e-textile products' prototyping and production tools. We see an opportunity in creating production-capable e-textile solutions.

6 CONCLUSION AND FUTURE WORK

The study interviewed 7 subject matter experts to understand their first-hand experience bringing e-textile projects to low-volume production. Although e-textile techniques have been explored for decades in research labs and STEM education settings, bringing them into production is still challenging for researchers, makers, and startups. E-textile production remains a technical challenge, as evidenced in previous studies [18]. Our study revealed opportunities for future research on tools, materials, and community support for low-volume e-textile production. Ultimately, we envision that low-volume e-textile production with lower barriers could enable more creators to bring their creations to broader audiences.

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