A review of connectors and joining technologies for electronic textiles

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Abstract
Reliable connections between electronic circuits remain a challenge in electronic (e-) textiles, where circuitry and components are embedded into clothing and other soft objects. E-textiles that can measure physiological signals, deliver medical interventions, or act as a human-computer interface are becoming increasingly pervasive, and the market for such products is predicted to grow dramatically in the coming years. Despite market predictions, several technical and production challenges persist, and these need to be overcome in order to realize commercial success. Challenges include a lack of standards for materials and manufacturing methods, issues with durability and washability, and incompatibility between textiles and electronic manufacturing methods. Joining technologies are a central part of this, as connecting e-textile parts in a way that is electrically reliable and durable, without negatively impacting the form, fit, and function of a garment is challenging. This article reviews key joining technologies used in e-textiles to date, demonstrating that few solutions have been specifically developed for e-textile applications. Existing solutions are mostly connectors designed for use in rigid electronics, or textile closure mechanisms adapted to work with e-textiles. A need for development of new joining technologies for e-textiles, as well as further research into the performance of existing methods is highlighted.

Keywords
connectors, e-textiles, flexible electronics, smart textiles, wearables

JEL Classification
Electrical and electronic engineering

1 | INTRODUCTION

Electronic textiles, or e-textiles, have started to cross over from idea to reality in recent years, but are still at an early stage of development. Although efforts to embed electronics into clothing began as early as the beginning of the 20th Century,¹ it is only in the past two decades that advances in material and manufacturing techniques have made the production of
commercial e-textile products possible. Products, such as those for tracking physical activity and sports performance, have not yet seen widespread adoption, but are growing in number.

As an emerging field, there is not yet a consensus on e-textile terminology. Other terms that describe, or overlap with, e-textiles include smart garments, intelligent textiles, wearable electronics, textronics, and electro-textiles. BSI Technical Report ISO/TR 23383:2020 recommends standard definitions and categorizations for this field, and based on this advice we use the following definitions:

- **E-textile**: A garment or other textile product that contains embedded electronics, whether the circuitry is made of textile components or more conventional electronic circuitry.
- **Electrically conductive textiles**: Textiles that either contain conductive fibers or are coated with metal or a conductive polymer, out of which e-textile circuits may be constructed. Also referred to in this article as just “conductive textiles.”

It is not difficult to see the challenge in realizing e-textiles: clothing is flexible, must bend and stretch repeatedly with the body, and be washed regularly. Electronic devices are usually rigid, and not washable. A major issue is the interfacing of electronic parts in e-textiles, whether in the joining of soft materials, or the creation of connections between hard and soft materials. The progress to date on overcoming these challenges is the focus of this article.

Before discussing e-textile joining technologies, it is useful to briefly review e-textile applications and different methods to construct e-textiles, to understand the criteria that must be met by such joining technologies. A 2020 review of “smart electro-clothing systems” shows that the two leading categories of commercially available e-textiles are sports and healthcare. In healthcare, e-textile medical devices can measure physiological signals such as electrocardiography or deliver various forms of treatment. Or rehabilitation, as in Connexstyle: Techstyle for Rehabilitation, a prototype muscle activity and movement monitoring garment developed by Jessica Smarsch with Fraunhofer IZM, POL Studio and Knitwear Lab. Beyond sports and medical applications, other products provide new ways to interact with technology, for example, by turning a jacket sleeve into an interface for controlling a smartphone. Others seek to augment human sensory ability, such as CuteCircuit’s SoundShirt, which uses embedded haptic actuators to allow the wearer to feel music instead of, or as well as, hearing it. Garments with embedded LEDs for lighting or wearable displays are another application category, and electroluminescent fabrics have been realized through printing with functional inks, weaving with luminescent fibers, or embedding LEDs inside yarns. Heated clothing is another area of interest, with applications in protective clothing and winter sports. Examples of e-textile commercial products, research prototypes and design concepts are shown in Figure 1.

Do-It-Yourself (DIY) kits and tools also enable e-textiles to be created outside specialized labs, including the LilyPad Arduino, Loomia Packs & Parts, and extensive documentation on e-textile construction methods by Kobakant.

Although there have been several articles and book chapters reviewing e-textile joining technologies, they have either focused on detachable connections or were published over 6 years ago, and as such do not cover more recent developments in a rapidly advancing field. This review takes a broad view of the e-textile landscape, covering academic research, commercial products, and work by individual designers and makers. It focuses on wearable applications rather than non-wearable e-textiles, such as those used in interior architecture and automotive applications. The e-textile artist duo Kobakant have also compiled extensive open source documentation of e-textile joining technologies, focusing on craft and DIY practice.

## 2 E-TEXTILE CONSTRUCTION

### 2.1 Joining technologies

In this article the term “joining technologies” will refer to all methods and materials used to make contact between parts of a circuit. These have been divided into two categories: a) detachable joining technologies, usually called connectors: these are typically electromechanical components such as snap fasteners or USB connectors, used for functions such as attaching a power source to an e-textile garment; and b) fixed joining technologies such as stitching or soldering, used for example to attach electronic components to flexible substrates. Fixed in this context means that the connection is not easily detached and reattached, not that it is physically impossible to remove the connection. A solder joint can be
reworked, for example, and stitches can be undone, but not with the same speed or ease that a snap fastener or USB cable can be connected and disconnected. Figure 2 shows examples of two different joining technologies used in e-textiles and highlights common joining terminology, also described in Table 1. There are many more ways to characterize joining technologies, but these are the most relevant to e-textile applications which are usually battery powered and involve low voltages.

Figure 2 also illustrates the fact that most, if not all, connectors are only detachable at one end: one end attaches permanently to a wire, fabric, or other conductive interconnect, and the other is detachable and may be connected and disconnected repeatedly. Thus any connector, which is a detachable, also needs a fixed joining technology such as soldering or crimping to fix it in place at one end.

A key challenge in e-textile joining technologies is balancing the trade-off between flexibility and reliability: many joining technologies rely on rigidity to ensure reliability, whereas garments must be flexible, with minimal rigid elements. This is particularly important for sports applications, as sports garments are typically lightweight and stretchable, and electronic circuitry added to sports clothing must not introduce rigid elements that could cause injury during motion or impact.
Joining technology terminology. (i) Pitch, (ii) detachable contact, (iii) connector housing, and (iv) fixed contact. A, An Amphenol FCI Clincher connector, featuring detachable pin contacts at one end, and “clincher” crimp connectors designed to make permanent contact with a flexible flat cable or flexible printed cable at the other end. B, A stitched connection to sewable contact pads on an Adafruit Flora microcontroller, an example of a fixed joining technology.

| Characteristic       | Description                                                                                                                                 |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| Number of contacts   | Contacts are the parts, usually metal, of a connector that form an electrical connection when brought into physical contact. They can range in numbers from 1 to several hundred in a single connector. |
| Pitch                | Distance between the centers of two adjacent contacts. Pitch can range from less than 1 mm up to several cm depending on the application, and standardized pitch values allow interchangeable use of electronic parts. |
| Gender               | Connectors often come in two varieties which “mate” to connect, traditionally called “male” and “female” but more recently the terms “plug” and “receptacle” have been adopted |
| Mating cycles        | How many times a connector can be connected and re-connected, ranging from one mating cycle up to tens of thousands, depending on the connection mechanism |
| Contact resistance   | Resistance introduced into circuit by the interface between contacts, which is influenced by several variables including the force applied to the contacts, the materials they are made from, and their surface roughness. |

Joining technology requirements depend on the specific application: connectors used inside smartphones need to be as small as possible, but need not be as robust as a connector for a household appliance power cable. A connector for a radio frequency signal may need to be shielded to protect from electromagnetic interference, and an e-textile connector will need to be washable or waterproof. Searching for connectors on the UK websites of the electronics suppliers RS Components, Farnell and Digikey returns 120,713, 581,369, and 2,217,975 results, respectively, which gives an idea of the variety of options available.

Despite the vast number of such products in existence, very few have been developed specifically for e-textiles. A few companies have produced connectors for “wearable” applications, but most focus more on non-textile wearable applications such as smart watches or other wrist-worn wearables, and very few are available for purchase off the shelf. Joining technologies for e-textiles also appear rarely within the literature on e-textiles, with many focusing on the development of novel textile sensors and e-textile garment platforms rather than the business of bringing a system-level solution together.

### 2.2 E-textile materials and construction methods

Before reviewing e-textile joining technologies, it is necessary to briefly review e-textile materials and construction methods. A variety of approaches have been taken to create e-textiles, and these are covered in depth across several existing reviews. Excluding early wearable electronics projects consisting of conventional electronics (bulky, rigid circuit boards connected by wires, and stitched into clothing or inserted into pockets), e-textile construction techniques can be loosely divided into three categories, examples of which are depicted in Figure 3.

1. Textiles as electronics (Figure 3A): This approach replaces traditional electronic circuitry with textile alternatives. Wires or printed circuit boards (PCBs) are replaced by conductive threads or fabrics, made from thin metal fibers...
or coated with metallic or conductive polymer layers. Conductive textiles can be woven\textsuperscript{30} or knitted\textsuperscript{31} into fabric, or embroidered\textsuperscript{32} or bonded onto it,\textsuperscript{33} to form conductive tracks. Conventional through-hole or surface mount components can be connected to conductive textiles, and some fully-textile sensors\textsuperscript{34,35} have been demonstrated.

2. Disappearing electronics in textiles (Figure 3B): The diameter of textile yarns (typically mm) sets a lower limit on the size of textile circuitry. But existing electronics fabrication methods can create flexible circuits at least an order of magnitude smaller. Thus another approach is to fabricate electronics on flexible substrates, for embedding inside textiles, whether in the seams, in pockets or channels,\textsuperscript{36} or inside yarns themselves.\textsuperscript{28} Another method uses small surface mount electronic components soldered to fine copper wire, and inserted into the core of an individual yarn.\textsuperscript{37}

3. New flexible materials for electronics (Figure 3C): Printing techniques including screen, dispenser and inkjet have been used in the textile and electronic industries for a long time but have recently been adapted to print directly onto fabrics using functional inks.\textsuperscript{7,8} Current e-textiles mostly still use traditional electronic components which, whether surface mount or through-hole, are rigid. Minimizing the size of these components reduces the impact of these rigid elements, but new research in nanotechnology and flexible electronics may eliminate the need for traditional components, and rigid PCBs, for example, with the development of inherently flexible ultra-thin devices.\textsuperscript{38}

4. Many examples of e-textiles are a combination of two or more of the above categories (Figure 3D). Zysset et al. wove flexible circuit modules into textiles with conductive thread bus bars.\textsuperscript{29} \textit{Closed-Loop Athleisure Fashion} features a rigid control module interfacing with printed sensors laminated onto the garment,\textsuperscript{39} which is an example of a standard format for e-textiles: flexible sensors are embedded into a garment, and a detachable rigid module houses the power supply and control circuitry.
3 | FIXED JOINING TECHNOLOGIES

3.1 | Stitched connections

Embroidery as an e-textile joining technology was first proposed by Post et al. Embroidering connections with conductive thread can be performed by hand or with a sewing or embroidery machine, and can be used to join conductive thread to other conductive thread, or to join conductive thread interconnects to PCB modules, as shown in Figure 4A. Linz et al. studied the reliability of embroidered connections, showing that connections can relax over time or in response to temperature cycling. They also identified strategies to improve connections, including triple sewing each connection, and adding additional pressure by adding encapsulation on top. Bartacking, a stitch type designed to reinforce areas of a garment that undergo high levels of strain, such as buttonholes or pockets, is mentioned by Tyler as a method for connecting conductive ribbon cable to a textile sensor.

Early investigations into e-textiles exploited the fact that holes in rigid PCBs designed for soldering through-hole components could also be used to sew connections with conductive thread, that is, some electronic components were sewable by chance. However, conductive thread is thicker than many regular threads, and needles with eyes large enough for conductive thread are sometimes too large to fit through holes in PCBs. The development of the Lilypad Arduino microcontroller pioneered the now common format of PCB modules for e-textiles featuring contact pads with large holes for sewing. Examples of these are shown in Figure 4E. Other methods pioneered by Buechley and still used by makers and craft practitioners to “make components sewable” involve bending through-hole component legs into sewable loops as shown in Figure 4D, or soldering jewelry crimp beads to surface mount components, enabling them to be easily stitched to fabric.

Machine embroidery with conductive thread can be challenging on standard embroidery machines, as conductive threads can be quite rough, or contain fine metal wires, which break or cause blockages in embroidery and sewing machines. The machine embroidery company ZSK Stickmaschinen has developed custom machinery in response to this, enabling sewable components to be automatically machine embroidered. They have also built on the concept of sewable components to develop circuit boards and functional LED sequins specifically designed for use with machine embroidery, as depicted in Figure 4B,C.
3.2 | Soldering

Soldering is a standard and widely used electronics joining technology. Two contacts are joined by melting a third metal, solder, which is usually an alloy with a melting temperature lower than that of the contacts to be joined. Soldering has been used in e-textiles to connect components to flexible substrates such as conductive thread, flexible copper wire, or polyimide, and examples are shown in Figure 5.

Soldered connections have low contact resistance but are mechanically brittle, and connections that are subject to any bending or stretching must be reinforced to avoid breakage in a textile application. As a manufacturing process, soldering can be done with easily accessible handheld equipment, but can also be scaled up to use high volume manufacturing techniques.

Some, but not all, conductive materials used in e-textiles are solderable. Stainless steel and silver-coated nylon threads, the most common conductive threads, are not solderable, but others composed of small diameter copper or brass wire, braided with heat-resistant carrier thread, are. Soldering to fabric or many printed electronic contacts often requires low temperature solder, as temperatures above 200°C, typically required for standard soldering, are high enough to burn or melt most fabric and many plastic films used in e-textiles.

Approaches to improve the strength of soldered connections to textiles have included laser soldering of components to copper wires, ultrasonic soldering, hot bar soldering, and increasing the permeation of conductive ink into fabric for soldering components to printed conductive tracks.

3.3 | Welding

Welding is a process used to join both metals and textiles, and in both cases, it involves localized melting of the materials to be joined. It is thus different to soldering in that it does not involve melting an additional material to form the connection,
but rather melting the materials themselves. Various welding methods exist, and these are explained in more detail in existing reviews. Welding is not a commonly used joining technology in e-textiles. Post et al. used spot welding to connect stainless steel threads to component leads. Spot welding is a form of resistance welding, where the materials are melted by the heat generated when current is passed through them. Muth et al. also used resistance welding to join components to conductive textiles, and more recent work has used it to weld conductive threads made from polyester and fine brass microwire, as an alternative to stitched connections.

3.4 Crimping and related methods

In electronics, crimping is the process of deforming a metal barrel around a conductor (usually a wire) to form a gas-tight, permanent connection. Sometimes called cold welding, it is a method commonly used in the automotive industry. For clarity, crimping is a fixed joining technology, but there are many (detachable) connector products which may be described as crimp connectors. These usually use crimp terminals to create permanent contact with a flexible substrate at one end, and have a connector such as pin headers at the other end. As shown in Figure 6B, crimp connectors by Nicomatic have been used to attach to conductive ribbon cable (a textile ribbon with embedded wires or conductive textile tracks). Crimp contacts are also used in the Amphenol FCI Clincher connector, depicted in Figure 2 and discussed in more detail in Section 4.4. Novel crimp connections have been developed for e-textiles by Fraunhofer IZM, where crimp terminals connect to conductive fabric or threads instead of wires, as shown in Figure 6C. A slightly different approach by Simon et al. proposes a force-fit interconnection method for e-textiles, where conductive textile contacts are sandwiched between rigid PCBs, using a screw to maintain pressure between the conductive textile contacts and contact pads on the rigid PCBs.

Another joining technology involving the permanent deformation of metal parts is that of rivets or eyelets, which are used in both electronics and textiles. Rivets and eyelets are small metal cylinders that are inserted into a hole in a PCB or a garment and flattened to create a tight contact. Rivets are used in electronics to create vias between sides of a two-sided PCB, and in textiles to add strength to parts of garments that undergo repeated strain, such as pockets. They have been used in e-textiles to join two sides of a fabric PCB, or a textile antenna. Lastly, insulation displacement connectors (IDC) have been investigated for use in e-textiles. This method involves slotting an insulated wire into tight contact, which deforms the wire, stripping the insulation from to form electrical contact. Not widely used, it is compatible with e-textiles that use wires as interconnects, less so with conductive fibers and printed tracks.

3.5 Adhesives

Several types of adhesive bonding are used in electronics, the most common in e-textiles being a) non-conductive adhesive bonding (NCA), b) isotropic electrically conductive adhesives (ICA), and c) anisotropic conductive adhesives (ACA).
Adhesive bonding has the advantage of lower curing temperatures than soldering requires, making it suitable for a wider range of fabric applications. Conductive adhesives also have the potential to replace lead-based solder with more environmentally friendly alternatives. The trade-off is that these typically have higher contact resistance and lower mechanical strength than soldered connections, but future developments in material science may change this.

NCA bonding, used in flip-chip assembly, has been adapted by Fraunhofer IZM to contact rigid circuit modules with conductive textile interconnects, shown in Figure 7A,B. A thermoplastic film is sandwiched between a rigid PCB module and conductive threads coated with thermoplastic. Under force and heat, contact is made between the PCB contact pads and the conductive cores of the yarns, and curing the adhesive maintains pressure on this connection. The method has been refined and a custom textile bonding machine has been developed.

ICA bonding involves adding a conductive filler to an adhesive material, for example, silver flakes added to epoxy. ACA is similar, except that the concentration of conductive filler is much lower. This means that when ACA is sandwiched between two contacts stacked on top of each other, ACA conducts electricity in the vertical (z-) direction, but the concentration of conductive particles is not high enough to conduct in the x-y plane. This makes it suitable for fine-pitch connectors, and means it is sometimes called z-axis tape/film, but also means it has higher contact resistance than ICA. Illustrations and examples of ICA and ACA bonding methods are shown in Figure 7A, and conductive adhesives are reviewed in more depth by Aradhana et al.

ICA has been used to connect conductive threads with copper-plated polyimide circuits (as depicted in Figure 7C) and copper wires. Komola et al. used ACA to attach small surface mount components to flexible electronic modules, but found it less reliable under bending than an alternate method using solder paste in combination with an underfill adhesive. Choi et al. explored ACA as a means to realize “chip-on-fabric” connection of silicon chips to textiles, noting issues with higher contact resistance than other joining technologies. Varga et al. used ACA tape to connect conductive thread interconnects with flexible electronic modules fabricated on polyimide (as shown in Figure 7D), but also found it to introduce significant contact resistance into the circuit. Jung et al. showed that using ACA film with copper rods instead of spherical conductive particles could reduce contact resistance, and the company Conductive Transfers have used ACA to join screen-printed conductive tracks that cross seams in garments.
4 | DETACHABLE JOINING TECHNOLOGIES, OR CONNECTORS

4.1 | Snap fasteners

Snap fasteners, also called gripper snaps, press studs, poppers, or press fasteners, are by far the most used connector in e-textiles. Snaps exist in several different varieties as shown in Figure 8: A) rivet snaps, which have prongs that secure the snap to fabric when applied with a special tool; B) sewable snaps, which are stitched onto fabric; C) experimental prototypes such as 3D printing directly onto fabric using conductive filament. Snaps with a flat base, which can be soldered or glued in place, or snaps with a crimp terminal for attachment to wire, are also available.

Despite their popularity, limited research has been carried out on the suitability of snap fasteners as electronic connectors. One study reported preliminary positive results on the use of snap fasteners as connectors for low and medium bandwidth signal transmission along conductive textile transmission lines. And standards do exist for snap fasteners, but only on their mechanical resistance when used a garment fastener. Standards and further research are required to assess, for example, the number of mating cycles they can survive as an electronic connector.

FIGURE 8 Snap connectors. A and B, Snaps used as modular connectors in Embodied RF Ecologies by Afroditi Psarra. Reproduced with permission. Copyright Afroditi Psarra. C, LilyPad SimpleSnap microcontroller with built-in snap contacts. Reproduced under the terms of the CC-BY license. Copyright Sparkfun. D, Printed conductive snaps by Rachel Freire Image shows a standard rivet snap (left) and an experimental snap 3D printed directly onto fabric (right). Reproduced with permission. Copyright Rachel Freire
4.2 | Pogo pins and magnets

Pogo pins are used in rigid electronics applications such as connecting a camera body to a lens, or for charging, as seen in many Apple laptop chargers. Figure 9 shows a cross-section of a pogo pin, which consists of a spring-loaded pin, and is designed to mate with a flat contact pad.

External pressure is required to bring the two in contact with each other to make an electrical connection. Magnets are commonly used for this, or pogo pins can be housed inside a press-fit plastic enclosure as seen in the Smart Socks by Sensoria. Magnets are also used as a temporary connector in the Threadboard prototyping kit, discussed in more detail in Section 4.2.

4.3 | Conductive hook and loop (Velcro) and other textile closure mechanisms

Silver-plated hook-and-loop (Velcro) is commercially available but has not seen widespread use in e-textile applications. Figure 10A,B shows conductive hook and loop and an example use of it in a light-up bag. In 2013, Locher stated that the
contact resistance of conductive Velcro is inconsistent, as the number of hooks and loops coming into contact with each other varies when the two parts are connected, and that the conductive coating tends to peel off quickly. In the same year, Seager et al. showed that strips of conductive Velcro could be used as flexible radio frequency connectors in the range of 500 MHz to 4 GHz, and showed that electroplating with copper increased the conductivity. Conductive hook and loop has also been investigated as a connector for automotive systems, an application with high levels of vibration, and enhanced with carbon nanotubes to reduce contact resistance. Commercially available conductive Velcro from companies such as Light Stitches claims surface resistivity of 1 Ohm/cm and up to 10,000 mating cycles.

Zippers and buttons, two common textile closure mechanisms, have also been adapted into e-textile connectors of sorts. In the case of the zipper, closing the zipper connects two electrical contacts, either by using the two sides of a metallic zipper as contacts themselves (as shown in Figure 10C,D), or by using a plastic zipper to press together two contacts made from conductive textile. The appeal of these types of connectors lies in the fact that they blend functional circuitry with features users expect to see in a garment. They enable e-textile clothing to look and feel like clothing, rather than electronic devices. The zipper connector has appeared in patents and a NASA technical report in the early 2000s, and more recently as a commercial product. Button connectors, as documented in the book Open SoftWear, work on the principle of a metal button making contact with conductive thread sewn around the buttonhole. These do not appear as popular as zippers, likely because the connection created is looser and therefore less reliable.

4.4 Pin headers and flexible electronics connectors

Pin headers are commonly used in rigid electronics for stacking PCBs or connecting sensors or flexible circuit modules to a rigid PCB. In e-textiles, they have been used to interface between soft circuits and rigid modules, and can be soldered to conductive fabric or to solderable conductive thread. Pin headers typically have 2.54 mm pitch, but other pitches
A range of connectors exist for use with flexible electronics; both flexible printed circuits (FPC) and flexible flat cables (FFC), usually to connect a flexible interconnect to a rigid PCB. Of these, the Amphenol FCI clincher series has been used in e-textile applications and is shown in Figure 11C–E. It has been demonstrated as a connector for e-textile ribbon cable with 2.54 mm pitch, conductive tape traces adhered to fabric, as a modular connector for copper conductive fabric traces in the Flex-Ability kit. The FCI clincher has crimp-style connectors on one end that make a fixed connection with fabric or flexible plastic substrates, and a male or female pin header contact at the other end.

### 4.5 Wireless connections

Wireless communication is an established method for transmitting power or data in electronics, for example, wireless smartphone charging using inductive coupling, or near field communication (NFC) between electronic devices. Inductive coupling has been proposed as a method to enable 3D integration in integrated circuit technology, or as a connector for smart glasses, where power and data must be transmitted across hinges.

Several examples of inductive coupling for wireless power transfer have been demonstrated for e-textiles, as shown in Figure 12. Heo et al. stitched conductive thread coils into fabric, and achieved wireless power transfer from a distance of 15 cm, up to a bending radius of 50 mm. Li et al. screen printed inductors onto fabric, which had lower efficiency compared to copper coils, but increased flexibility which is beneficial for textile applications. Zhu et al. proposed a three-coil structure to overcome efficiency issues from coil misalignment, using a coil of thin copper wire stitched into fabric with a covering thread. Other inductor geometries that may see use in e-textiles include knitted helical coils which can be integrated into fabric itself, and fractal or space-filling inductors which have been demonstrated on flexible substrates. Wireless connection for data transfer has been demonstrated using NFC by Lin et al., who created a garment with embedded sensors and textile antenna coils that send data to a smartphone.

### 4.6 Connectors for prototyping and testing

The need for rapid prototyping and testing tools for e-textiles has led to the creation of several e-textile kits and prototyping connectors. Standard electronics prototyping processes, such as using a solderless breadboard and jumper cables, have limited compatibility with e-textiles. Sewing a prototype with conductive thread is time-consuming and does not
support quick design changes, and conductive thread or other flexible interconnect materials often have significantly higher resistance than breadboard jumper cables. Alligator clips are commonly used for e-textile prototyping, and many e-textile products such as the Adafruit Flora feature large contact pads which are designed for clipping alligator clips to before sewing or soldering a fixed connection, as shown in Figure 13A. However, alligator clips and other standard tools such as multimeter probes, grabbers or spring hook clips can be difficult to attach to e-textiles, and can also cause damage to delicate fabrics.

Posch et al. explored these issues in depth and proposed designs for new tools that merge standard electronics tools with textile tools such as pins.97 One of these is the Pin Probe, which combines a 4 mm banana plug, para-cord, conductive thread, a pin, and 3D printed parts to create a connector which can be inserted into a multimeter at one end, and pinned into the fabric at the other, creating a useful tool for probing connections on fabric circuits. Similarly, the Fabric Pinch Clip adds conductive tape to a plastic sewing clip to create a fabric-compatible cable.
These connectors are shown in Figure 13B,C. Building on this work, safety pin crocodile clips by Rachel Freire,99 shown in Figure 13E provide another way to interface between traditional electronics prototyping tools and fabric circuitry. Pins have also been used by Afroditi Psarra to make custom connectors to test an e-textile antenna, as depicted in Figure 13D. The Tools We Want project100 proposes additional tools for e-textiles that merge electronics and textile practice.

Threadboard,73 shown in Figure 13F, is an e-textile prototyping kit that takes a different approach, using a grid of magnets to route conductive thread and connect it to components. This is suitable for prototyping e-textile projects using conductive thread, and facilitates prototyping using the same materials as will be used in the finished product. Conductive fabric tape, usually conductive fabric with a conductive adhesive backing, can also be used to create rapid e-textile prototypes.101 A novel connector demonstrated by Li et al., and designed for use with standard through-hole components, consists of a coil of conductive thread encased in resin.102 It is proposed that this connector allows components to be removed for washing, as components can be inserted and removed as needed. This could be useful as a kind of fabric breadboard, but for use in a commercial product would be inconvenient for an end user to remove all components and then replace them on every wash.

5 | DISCUSSIONS

5.1 | Joining technology reliability

Several organizations are developing standards for e-textiles,103-105 but in the current absence of standards, it is difficult to directly compare joining methods. As such, reliability in e-textiles is not well-defined, but typically includes resistance to bending, stretching, sweat, washing, humidity, and temperature cycling. Reliability requirements vary for different applications, for example, a fashion garment can be hand washed, whereas a medical garment needs to survive machine washing at 90°C. Some connectors used in e-textiles have been designed to meet standards for either the textile or electronics industries, but others have not. Despite the lack of standards, a couple of common connector design features
and reinforcement techniques have emerged, specifically the use of rigid control modules in a protective housing, and encapsulation of components and circuit modules.

5.1.1 Rigid control modules

Most current e-textiles follow a similar format: flexible sensors or actuators are embedded into the garment, and control circuitry and a power source are housed in a rigid module attached to the outside of the garment. Figure 14 shows a variety of designs used for this, and other examples have already been shown in Figures 1 and 9. Different examples use press-fit, twisting, or slide-locking mechanisms to attach the rigid module to the garment. Military applications, which must be extremely rugged, can feature multiple locking mechanisms. A key aspect of the rigid control module is its protective housing: almost all are enclosed in a plastic case, some featuring a brim on the garment part of the connector, to provide strain relief at the interface between flexible embedded sensors and the rigid module. USB connectors are sometimes used to connect rigid modules or power sources to an e-textile, but snaps, pogo pins, or custom connector designs are more commonly used.

An alternative design proposed by Mehmann et al. features a ball-grid array connector that consists of two parts: a textile pocket lined with conductive fabric contacts, and a rigid electronic module with raised contacts. The rigid module is inserted into the pocket, and the fabric pocket stretches, maintaining pressure between the contacts on the rigid module and the corresponding conductive fabric contacts.

**Figure 14** Interfacing rigid modules with embedded textile circuitry. A, illustration of how rigid control modules are used in e-textiles. Reproduced with permission. B, Levi's® Commuter™ Trucker jacket with Jacquard™ by Google, featuring a USB tag that attaches to the jacket cuff. Reproduced with permission. C, Washable connector by Ohmatex. Reproduced with permission. Copyright Ohmatex. D, Mag-net connector system by TT Electronics, designed for military applications. Reproduced with permission. Copyright TT Electronics.
5.1.2 Encapsulation

Encapsulation involves covering a component or connection with a layer of protective material, typically epoxy. Examples of encapsulation methods are shown in Figure 15. To encapsulate individual components, “glob-top” encapsulation is often used. A droplet of encapsulant is applied on top of a component, for example a surface mount component on a flexible PCB.\(^{29,44}\) Linz et al. used molding to form a protective layer of epoxy over a flexible PCB, which helped reduce the contact resistance of embroidered connections to the flexible PCB.\(^{40}\) Wagih et al. also used a molding process, to mold a polyimide encapsulation layer for a polyimide RFID tag, and bonding the two layers together with adhesive.\(^{109}\) Nashed et al. molded a cylindrical resin micro-pod around components soldered to copper wire, before embedding inside a yarn.\(^{37}\) More accessible materials such as fabric glue, puffy paint and clear nail polish are used by craft practitioners to secure knots of conductive thread and insulate conductive textile connections.\(^{110}\)

5.2 Choosing a joining technology

Ultimately, choice of joining technology requires consideration of many factors, and weighing up what is most important for the intended application. Tyler\(^{22}\) summarizes useful criteria for choosing a joining technology for e-textiles: physical strength, electrical reliability, ease of attachment, repeatable re-attachment, aesthetics, size, comfort, cost, and availability. To this list, it is necessary to add: a) what kind of electrical signal is being transmitted, that is, signal or power; b) the stage of development of the product, as a joining technology that requires custom machinery will not be suitable for a one-off prototype, but one that is time-consuming to install will not suit a product ready for batch manufacturing; c) the limitations of the fabric used in the e-textile garment, as some fabrics will require joining technologies that can be done at low temperature or room temperature.

Tables 2 and 3 give general comparisons of e-textile joining technologies. As illustrated in the previous sections, these joining technologies are either standard components or processes from the electronics and textile industries which have been adapted for use in e-textiles, or are custom one-off products or prototypes. Some have been tested against standards for rigid electronics, or textiles, or subjected to bespoke tests to assess the effects of humidity, temperature, washing, or mechanical strain such as bending or stretching. As standard tests for e-textiles have not yet been developed, a full quantitative comparison is not yet possible. But as multiple organizations are developing e-textile standards, it is hoped that more quantitative data on e-textile joining technology performance will be obtainable in the near future.

![Figure 15](image_url) Encapsulation of connections. A, Molding a polyimide encapsulation layer for an antenna circuit fabricated on a polyimide substrate. Reproduced under the terms of the CC-BY license.\(^{109}\) Copyright 2020, the authors, published by MDPI. B, Encapsulating single components using resin molding. Reproduced under the terms of the CC-BY license.\(^{37}\) Copyright 2019, the authors, published by MDPI. C) Epoxy molded onto a chip on a “planar fashionable circuit board” on fabric. Reproduced with permission.\(^{55}\) Copyright 2010, IEEE. D, Epoxy molding of a flexible PCB. Reproduced with permission.\(^{40}\) Copyright 2005, IEEE. E, glob-top encapsulation of an ICA connection between conductive thread and copper-plated polyimide. Reproduced with permission.\(^{29}\) Copyright 2012, IEEE
### TABLE 2 Comparison of fixed joining technologies

| Name                        | Method of attachment                                      | Compatible with                      | Durability                                                                 | Advantages                                                          | Disadvantages                                                                 | References |
|-----------------------------|------------------------------------------------------------|--------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------|--------------------------------------------------------------------------------|------------|
| Machine embroidered conductive thread | Embroidery machine. For some conductive threads, or more complex designs, specialist machinery required. | • Textile  
• Rigid PCB with sewable pads  
• Flexible PCB  
• Wire | Can be damaged by temperature (affecting contact resistance)  
Conductive coating can flake off during washing | • Compatible with most textiles  
• Scalable with right equipment  
• Flexible  
• Looks and feels like textile | Durability is not well studied  
Temperature and washing can relax connection  
Specialized machinery  
Not suitable for joining discrete electronic components directly  
Some conductive threads not compatible with standard embroidery machines | 32,40,41 |
| Hand stitched conductive thread | Hand sewing tools (needle and conductive thread)          | • Textile  
• Rigid PCB with appropriate sewable pads  
• Flexible PCB  
• Wire | Preliminary washing tests show continued function after washing at 20 °C | Does not require specialized equipment or technical knowledge | Reliability not well documented, but expected to be lower than machine stitching  
Time consuming, therefore not suitable for manufacturing at scale | 33 |
| Soldering                   | Soldering equipment, heat. Typically above 250 °C, low temperature options still require >150 °C | • Rigid PCB  
• Metal wire  
• Limited conductive textiles  
• Some conductive inks  
• Standard components | Strong electrical connection  
Not flexible, requires protection against breakage at interfaces between solder joints and flexible substrates | • Compatible with standard electronics processes  
• High availability  
• Adaptable to both high and low volume production | High application temperature even with low temperature solder paste  
Not compatible with many conductive textiles  
Not flexible | 37,43,44 |
| Welding                     | Heat (produced as a by-product) Welding equipment.        | • Some conductive textiles  
• Metal wires | Contact resistance $\leq$1 Ohm  
Requires encapsulation to survive washing | • Compatible with wider range of conductive threads than soldering (e.g., stainless steel thread) | High temperature can damage delicate textiles and some printed conductive tracks on textiles | 32,49,50 |
| Crimping and rivets         | Crimping tool (manually operated or automated)            | Depending on product:  
• Textiles  
• Rigid PCBs  
• Flexible PCBs  
• Wires | Preliminary evidence of washability  
Supports repeated connection/disconnection | • Room temperature application  
• Compatible with both high and low volume production | Not compatible with all types of e-textile material  
Some types of crimp connector do not survive washing | 53-55 |
| Adhesives: NCA              | Heat and pressure, supplied by die bonder or custom equipment. | Bonding rigid modules or components to conductive textiles or wires | Resistant to temperature and humidity cycling | Demonstrated to work with 1.27 mm pitch components | Requires die bonder or custom equipment  
High bonding temperature (197 °C) | 57,59,60 |
| Adhesives: ICA              | Some variants are heat curable, others cure at room temperature. Applied manually or dispensed by machine. | • Textiles  
• Rigid PCBs  
• Flexible PCBs  
• Standard components | Encapsulation is required to prevent breaking | • Lower curing temperature than soldering  
• Compatible with printed conductive tracks | More mechanically brittle than soldering  
Higher contact resistance than soldering  
Absorbs moisture if not encapsulated | 29,61,62 |
| Adhesives: ACA              | Can be cured at room temperature. Heat or pressure reduce cure time. Applied manually or dispensed by machine. | • Textiles  
• Rigid PCBs  
• Flexible PCBs  
• Surface mount components | Mechanically strong but electrical connection unreliable under strain | • Suitable for components with very fine pitch  
• Low curing temperature | High contact resistance relative to ICA or soldering  
Inconsistent contact resistance under strain | 44,58,64 |
| Name                  | Method of attachment | Compatible materials | Durability                                                                 | Advantages                                                                 | Disadvantages                                                                 | References |
|----------------------|----------------------|----------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|------------|
| Snap fasteners       | Sew, crimp or solder, depending on variant. | • Textiles<br>• Rigid PCBs<br>• Flexible PCBs<br>• Wires | • Produced as a long-lasting garment fastener. Electrical durability not tested. | • Widely availability<br>• Mechanical durability<br>• Protective enclosure not needed<br>• Attachment can be done by hand or automated | • Relatively large footprint (typically 10 mm diameter per contact)<br>• Electrical characteristics not well studied | [32, 69] |
| Pogo pins            | Solder to rigid PCB  | • Rigid PCBs | • 10,000 mating cycles<br>• Contact resistance 20mΩ | • Small footprint<br>• Low contact resistance when properly mated. | • Require sturdy housing to maintain contact which can be bulky. | [111] |
| Magnets              | Conductive adhesive | • Textiles<br>• Rigid PCBs<br>• Wires | Not defined | • Contact maintained without additional mechanical support | • Limited data on suitability as an electronic connector | [71, 73] |
| Conductive hook and loop | Sewing or adhesive | • Textiles | • 10,000 mating cycles<br>• Contact resistance unclear | • Possible inconsistent contact resistance | • Not extensively studied<br>• Large footprint<br>• Consistency of contact resistance not quantified | [76, 77, 79] |
| Zipper               | Sewing              | • Textiles | Not defined | • Looks like clothing rather than electronic component | • Electrical properties not tested | [80-82] |
| Button               | Sewing              | • Textiles | Not defined | • Looks like clothing rather than electronic component | • Not robust enough for use as a proper joining technology | [83] |
| Pin header           | Soldering            | • Some conductive textiles<br>• Rigid PCBs<br>• Wires | • 50–300 mating cycles depending metal used to plate contacts | • High availability<br>• Standard pitch compatible with other components<br>• High mating cycles | • May disconnect easily inside clothing (not tested)<br>• Not tested for use in textiles | [33, 84, 112] |
| Amphenol FCI clincher | Crimping             | • Flexible PCBs<br>• Some conductive textiles | • 100 mating cycles<br>• Mating/unmating force 300g / contact<br>• Contact resistance 20mΩ<br>• Preliminary evidence suggests ability to survive 50 wash cycles | • 2.54 mm pitch compatible with standard components<br>• Compatible with both low and high volume production<br>• Low contact resistance | • Not designed for use in e-textiles, may disconnect easily inside clothing<br>• Not compatible with all e-textile interconnect materials | [53, 86-88, 113] |
| Wireless             | Stitched or printed onto fabric | • Textile<br>• Rigid PCBs<br>• Flexible PCBs | Preliminary evidence of washability<br>• Highly flexible | • No physical connection required<br>• Flexibility | • Signal loss/lag<br>• Inductive coupling requires AC signal and additional electronics | [91-94] |
| Alligator clips      | Not applicable       | • Textiles<br>• Rigid PCBs | Can be attached/removed repeatedly<br>• Contact with very thin or delicate materials can be unstable | • Availability<br>• Quick to attach and remove<br>• Useful for prototyping and testing of connections | • Relatively bulky<br>• Jaws can cause damage to textiles<br>• Not suitable beyond prototyping stage of development | [97] |
| E-textile prototyping connectors | Not applicable | • Textiles | Not tested | • High compatibility with textiles<br>• Useful for prototyping | • Not commercially available, must be custom made<br>• Durability not tested | [97, 99] |
Some e-textile kits provide for the need for different joining technologies at the prototyping stage compared to a finished product, as shown in Figure 16. Prototyping parts by Loomia have breadboard-compatible contacts that can be used for prototyping, and then cut off so that fixed connections can be made to a separate set of contacts by soldering. Textile Prototyping Lab’s e-textile kit takes a slightly different approach, with rigid PCB modules with sewable contacts for making garment prototypes. For higher volume production, these contacts can be removed, reducing the overall size of the module, and components connected to conductive fibers using NCA bonding instead.

5.3 | Sustainability considerations

Seamless integration of electronics into textiles is often cited as the ultimate goal of e-textiles, that is, garments where the electronic circuitry is completely undetectable by the user. However, realizing this goal may have negative consequences for sustainability, as it makes repair or recycling of an e-textile product more difficult. Köhler points out that when e-textiles break through to mass markets, this will create a new waste stream of products that cannot be recycled in either textile or Waste Electrical and Electronic Equipment (WEEE) recycling.

Hardy et al. argue for modular design in e-textiles, where electronic circuitry and textiles with relative ease. They highlight the fact that the Levi’s® Commuter™ Trucker jacket with Jacquard by Google, which has touch sensors embedded in the jacket’s left cuff, can only be washed 10 times, which is a low number for a denim garment which would typically last for 5 years. Others have suggested business models for e-textiles that are based on leasing garments rather than selling them, so that manufacturers can use their specialist knowledge to repair and reuse e-textile circuitry.

Although the issue of sustainability in e-textile is much more than recycling and reuse, prioritizing modular design means that connectors have an important role to play in the sustainability of e-textiles. Most current e-textile products are modular to some degree, as they feature detachable control modules that are attached to the garment and removed for washing. However, this could be extended so that circuitry embedded inside clothing is more easily disassembled, which
meansthat very small or flexible connectors need to be developed to potentially replace fixed joining technologies such as embroidery or soldering.

6 | CONCLUSION

This review provides an overview of joining technologies used in e-textiles to date. This includes detachable joining technologies or connectors, including snaps, pogo pins, conductive hook and loop, textile closure methods such as zippers, header pins, and wireless connection via inductive coupling or NFC. In the category of fixed joining technologies, stitching, soldering, welding, adhesive bonding, and crimped connections have been discussed. Connectors suitable for prototyping, and common designs for connectors used in commercial products have also been reviewed, as well as criteria to consider when choosing a joining technology. The environmental impact in terms of sustainability has been presented, including the role of connectors in promoting repairability and recyclability.

Finally, the lack of standardization of e-textile joining technologies makes it challenging for e-textile designers to compare different options and choose a suitable solution. For example, some joining technologies have well-defined contact resistance, whereas this has not been rigorously tested for others.

Overall, joining technologies are a critical but under-researched area of e-textiles, with current e-textile products relying largely on solutions adapted from rigid electronics, or from textile manufacturing, with some adjustments to make them work for e-textile applications. Investment into the development of novel e-textile connectors, as well as standards for the design and fabrication of e-textiles, are needed to enable the field of e-textiles to advance.

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CONFLICT OF INTEREST

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