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Cords and Chords: Exploring the Role of E-Textiles in Computational Audio

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Electronic textiles (e-textiles) have played a significant role in computational audio ranging from wearable interfaces for creative expression to more utilitarian purposes such as acoustic monitoring for military applications. This article looks at e-textiles within computational audio from three perspectives: the historical developments of the field; the core enabling technologies; and the primary application areas. It closes with a discussion of what role e-textiles may play in future computational audio systems.

Keywords: e-textiles, audio, electronics, wearable computing, digital musical instruments

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1. INTRODUCTION

At first glance there may appear to be few connections between computational audio and constructing electrical circuits from conductive textiles. The physical form of modern electrical circuitry is not often considered to be influential in the computations it is conducting. However electronic textiles (e-textiles) are firmly rooted in the physical. They are circuitry built of conductive threads and fabrics whose limitations and possibilities entirely lie in the physicality of textile materials and processes. Yet engineers, designers, musicians, and artists have been generating, manipulating, or sensing audio using e-textiles since the seminal publications in the field in the late 1990s. This paper examines those connections, surveying what role e-textiles have played in computational audio.

It is important to differentiate e-textiles from the broader term wearable technology. Wearable technology refers to computational devices which are worn on the body and are not restricted to a particular set of materials or manufacturing techniques. E-textiles are a collection of fabrication methods that use conductive threads or textiles to form electrical circuitry. We will expand our interest in e-textiles here to include circuitry built with traditional electrical components that are mounted on a textile substrate. E-textiles may be used for wearable applications, but as will be explored, they are also chosen for audio applications and devices that are not worn on the body.

This paper surveys over 50 computational audio projects that utilize e-textiles. We will start by looking at the history of e-textile research and development through the perspective of computational audio. The next section will present a technical overview of the textile fabrication techniques and the most frequently used e-textile sensors and actuators for audio generation and control. We will then examine common applications and why e-textiles are chosen to implement a circuit or interface. We close with a discussion of the current state of e-textiles for computational audio and look toward its future.

The survey search was seeded by searching for keywords of "fabric," "textile," and "thread" along with "audio," "sound" or "music" in proceedings from computer science and engineering communities such as the Association for Computing Machinery (ACM) Digital Library and Institute for Electrical and Electronics Engineers (IEEE) Xplore Digital Library, from arts technology conference communities including New Interfaces for Musical Expression (NIME) and International Symposium on Electronic Art (ISEA), and a Google Scholar search. Any relevant publications cited in publications resulting from those searches were also included. A similar search for relevant terms was conducted through the growing collection of textbooks within e-textiles design education (Seymour, 2008; McCann and Bryson, 2009; Buechley et al., 2013; Quinn, 2013; Ryan, 2014; Kettley, 2016), with citations to primary sources used here wherever possible. Looking toward performances and objects developed outside of academia, a search was also conducted through the portfolios of individuals who make up the eTextile Summer Camp community (eTextile Summer Camp, 2018).

2. HISTORICAL OVERVIEW

E-textiles were introduced as an academic area of research in the mid-1990s and have grown to be a topic of interest across numerous boundaries: arts and science; academia and industry; and designers and technologists. While the discipline has shown consistent interest in the ability to embed LEDs or other light-emitting technologies into textiles, it has an equally historic interest in embedding audio technology.

2.1. Early Research

E-textiles emerged from wearable technology research communities which were largely focused on medical and military applications. The MIT Media Lab was a significant hub of research on wearable computers, but while some students were working on systems that would be the predecessor to Google Glass, others in the lab started looking at integrating computation directly into conductive textiles (Ryan, 2014, Chapter 2). Post and Orth (1997) are credited with producing the first published research on e-textiles. They explored emergent conductive properties of metallic silk organza along with the repurposing of textile tools for creating electrical circuitry. As part of their research they developed a series of prototype systems exploring various interactions and outputs with music generation as one of the first use cases. Their MIDI Jacket was a denim jacket with touch-sensitive embroidery which controlled an embedded MIDI sythesizer (Post et al., 2000). Other projects worked with similar technology, integrating multiple pressure sensors into squeezable balls designed for musical performance (Weinberg et al., 2000). For a first person account of the developments at the time, see Orth's closing chapter in (Buechley et al., 2013) about the work and challenges of this era. The Media Lab continues through to the present day to explore e-textiles as interfaces for creative expression, largely as handheld objects to be manipulated through squeezing or stretching (Chang and Ishii, 2007; Wicaksono and Paradiso, 2017).

As early e-textiles research at MIT looked toward creative applications and fields such as fashion and design, researchers at other American institutions including Virginia Tech and Georgia Tech were investigating how audio processing within e-textiles could be used for more military-oriented aims (Marculescu et al., 2003). This included acoustic sensing through beamforming incorporated into large scale e-textiles (Nakad et al., 2007) and the Georgia Tech Wearable Motherboard designed for soldiers in the field which allowed for voice monitoring (Gopalsamy et al., 1999).

Elsewhere, creative applications for e-textiles were being explored, particularly as sensors to control musical expression within digital musical instruments (DMIs). Work from CNMAT at University of California Berkley focused on applying established, and perhaps previously overlooked, electrical engineering and signal processing techniques to conductive textiles (Freed, 2008, 2009; Schmeder and Freed, 2010; Roh et al., 2011) while researchers outside the USA explored how textile engineering could support both electrical and aesthetic aims within musical performance (Kettley and Briggs-Goode, 2010). These activities were supported by academic and artistic events such as reSkin (Barrass, 2008) in Australia which directly enabled the exchange of ideas from practitioners in the US and UK with Australian designers and engineers. Works exhibited included Felt Pods by Cecilia Huffer—felted sculptural objects illuminated with LEDs and optical fibers which generated sounds (Heffer, 2007).

Outside of academia, commercial research labs began showing interest in e-textiles from as early as 2000, though they seldom discussed technical details in publications about their projects. This time period is referred to as the "MP3 Jacket Craze" by McCann and Bryson (2009), though audio played a prominent role in many of these prototypes for a range of applications. Smaller fashion labels and design agencies including CuteCircuit and XS Labs explored integrating portable music player functionality into clothing, using conductive textiles to create soft loudspeakers, and turning garments into fully embedded synthesizers. Larger corporations such as Philips, Levi's, Nike, and O'Neill all developed prototypes embedding audio communication into clothing for applications like music players for outdoors sports and workwear with two-way voice communication. Seymour (2008) provides an extensive overview of the projects that were developed during this time.

2.2. Broadening Access Through the Lilypad

The mid-2000s brought about a revolution in who was conducting electrical engineering and computing research, which up to that point was restricted to those with formal engineering qualifications within academic or industrial research labs. The release of the Arduino microcontroller platform allowed electronics development and programming to be directly accessible to those interested in the interaction design of embedded electronics systems. As the Arduino was being developed, Leah Buechley in the Craft Technology Group at University of Colorado at Boulder released the E-Textile

Construction Kit which had its own microcontroller mounted on textiles that could be connected to other e-textile components (Ryan, 2014, Chapter 5). The project later evolved and adopted the Arduino environment for programming the microcontroller, resulting in the LilyPad Arduino (Buechley et al., 2008).

The LilyPad was commercialized and sold by Sparkfun, an electronics retailer also located in Boulder, Colorado who had a significant role in the establishment and growth of the Maker Movement (Buechley and Hill, 2010). The board can still be purchased worldwide from multiple suppliers. The LilyPad addresses some of the circuit construction issues highlighted by Post et al. (2000) regarding integrating electrical components into textile circuitry. It is manufactured as any other printed circuit board (PCB), but is circular with pads evenly arranged around the board like petals on a flower, which provide connections to the inputs and outputs of the microcontroller . Each pad has a hole large enough for a needle and conductive thread to pass through several times, providing a method for transitioning between the inflexible PCB and flexible textile. The low cost of the hardware and free availability of the supporting software opened up e-textiles to a far broader audience than ever before. It is a platform that is still used today and has influenced similar e-textile microcontroller platforms like the Flora by Adafruit which can be seen in **Figure 1**.

In 2009, Buechley started the High-Low Tech group within the MIT Media Lab. Until its closure in 2014, it was central to the development of e-textiles and related fields like paper circuitry. One of the lab's researchers was Hannah Perner-Wilson who along with Mika Satomi form Kobakant, an artist collective whose work with e-textiles greatly informs the larger e-textile design community. Kobakant document their projects and material experimentations on their website *How to Get What You Want* (Satomi and Perner-Wilson, 2011). Their approaches for constructing sensors, actuators, connectors, and electrical traces using hand-crafting techniques are frequently cited by artists and designers (Ryan, 2014, Chapter 5).

FIGURE 1 | Flora microcontroller developed by Adafruit and based on the LilyPad by Leah Buechley. It is connected to conducted thread and fabric circuitry.

As solutions for integrating electronics into textiles became more well known and related commercial products like the LilyPad more widespread, interface and interaction design could become a research focus as it was no longer necessary to be an electrical engineer to work with these materials and components. Researchers looked at how textiles could allow for novel interactions with music. Textile interfaces to control an audio player were developed such as interacting with a tubular knit structure worn around the body (Gowrishankar et al., 2011) or pinching and rolling fabric (Karrer et al., 2010) to play or stop a music playlist.

More conceptual artistic works were also produced such as a fabrics that react to sound (Heinzel, 2014) and a dress that could mourn on behalf of its wearer (Perner-Wilson and Satomi, 2012). E-textiles also more frequently appeared on the body not within a fashion context but within dance (Yang et al., 2011; Psarra, 2014; Dubrule et al., 2016; Sicchio et al., 2016).

In the 2010s, European funded artistic networks supported the exploration of the creative and performative aspects of e-textiles in relation to fine and applied arts. Notable networks include the METABODY network (METABODY, 2018) which supported the E-Textile Project held at STEIM in Amsterdam (STEIM, 2015a) It was an event that brought e-textile practitioners together to develop wearable devices for artistic performance and STEIM (the STudio for Elecro-Instrumental Music) regularly hosted activities such as workshops to develop e-textile interfaces for musical expression (STEIM, 2015b,c). While METABODY concentrated on performative aspects of the body, the Ambience conference series initiated by the University of Borås focused on the role of textiles within art and design (Ambience, 2011).

2.3. Current Research

E-textiles have found numerous uses across many fields ranging from fitness and sports to aeronautics. Common issues that arise from all applications areas and research disciplines are: the dependability and stability of e-textile sensors and actuators; the connection between flexible textile materials and inflexible electrical components; providing power to textile circuitry via batteries without impeding the characteristics of textiles such as flexibility; and overcoming manufacturing constraints to be able to produce e-textile products at scale. All of these difficulties have been encountered by the mi.mu Gloves (MI.MU Gloves Limited, 2018) and the range of jackets by Machina (Machina, 2018), two musical e-textile products that have been brought to market in recent years.

Google and Levi's undertook a partnership to tackle some of the manufacturing problems encountered when creating woven textile capacitive sensing interfaces (Poupyrev et al., 2016). Their Project Jacquard may be seen in the future as a turning point in the mass production of e-textiles, though at the same time it highlights how much research is still needed as the first commercial product from their collaboration has yet to see significant commercial success (Levi's, 2016).

As wearable technologies matured and became easier to integrate into consumer products, the WEAR Sustain network was established to support the development of new commercial ventures, with projects involving computational audio including mi.mu (MI.MU Gloves Limited, 2018), KOBA Tailor Shop (Kobakant, 2018b), and FlexAbility (Blumenkratz et al., 2018). A second European formal academic network of note is ArcInTex (ArcInTex, 2018), which doesn't explicitly focus on interactive audio, but does look at at interactive textiles in a variety of contexts.

Academic research in e-textiles is now world-wide and can be found across material science, computer science, electrical engineering, textile design, interaction design, fashion design, and many other communities. Listing individual research labs or even academic journals is impractical, but research at the intersection of computational audio and e-textiles is regularly published at the ACM International Symposium on Wearable Computing and ACM International Conference on Tangible, Embedded, and Embodied Interactions.

3. TECHNICAL OVERVIEW

A set of core techniques and technologies are commonly utilized when working with e-textiles for audio applications. This section will first review the textile fabrication techniques most commonly used and then how these techniques create sensors and actuators. It is not possible to provide an exhaustive description of all possible techniques as that is beyond the scope of this article, but (McCann and Bryson, 2009; Stoppa and Chiolerio, 2014; Dias and Ratnayake, 2015; Kettley, 2016) are recommended for additional reference.

3.1. Fabrication Technologies

E-textiles are textile structures with electrically conductive elements, and as textiles can be formed using a variety of techniques developed over millennia, there are multiple ways to introduce conductivity. Conductive threads are frequently used as they can be manipulated in a similar way as non-conductive threads. The most commonly used threads are metallized by either nano-plating or wrapping non-conductive core threads with silver, copper or steel, but yarns can also be constructed by spinning staple wool or polyester fibers with metal fibers similar to how non-conductive yarns are produced. Another method often employed is electro-spinning conductive polymer into fibers or coating non-conductive textiles with a conductive polymer solution (Qu and Skorobogatiy, 2015).

Conductive textile structures can be formed from these yarns by undergoing traditional textile processes such as weaving or knitting. Alternatively a non-conductive fabric can have conductive threads embroidered on top of it or conductive inks printed on it to form circuitry. A more recent approach is to work with electronic components that are so small, they can be directly integrated into a yarn which then can be embroidered, knit, or woven.

3.1.1. Knitting

Knitting is the looping of a yarn to form a fabric. A single thread or yarn can be used to construct an entire panel of fabric or even an entire garment. The structure of knit fabrics allow them to stretch and then return to their original shape when released. This makes them attractive for stretch sensors as are discussed below and for garments that are to be worn close to the body (Kettley and Briggs-Goode, 2010; Stewart and Skach, 2017).

Commercial conductive knit fabrics are now easily available for purchase online. The most common type is a Lycra that has been electroplated with silver. This fabric can be cut and sewn or bonded together with non-conductive knit fabric to form garments with integrated electrical traces.

The knit structure can also consist of multiple yarns, for example to form stripes as seen in **Figure 2**. Non-conductive and conductive yarns can be knit in alteration to form a designed circuit as done in the Musical Sleeve (Gowrishankar et al., 2011).

3.1.2. Weaving

While knit fabric can be made from a single continuous yarn, woven fabrics are made from a set of separate parallel threads called the warp. Another thread referred to as the weft is alternately woven above and below the warp threads creating a grid of perpendicular threads. This technique is particularly useful for running parallel traces through a textile as in Nakad et al. (2007). This woven structure within a metallized silk organza was exploited in the Musical Potholder and Keyboard by Post and Orth (1997). The warp threads were made of silk only, while the weft threads were silk wrapped in a thin copper foil. The woven structure kept the conductive threads electrically isolated from each other, so they could be treated as electrical busses for the microcontroller and other circuitry soldered on top.

Sheets of woven conductive fabric are commercially available; a nylon ripstop fabric nano-plated with silver or copper is the most commonly found, but **Figure 2** shows a commercial woven fabric from bamboo and silver fiber. It has a much lower electrical resistance than individual conductive threads, so is often found in circuits where a larger surface area of similar resistance is needed such as pressure sensor matrices (Donneaud et al., 2017).

3.1.3. Embroidery and Appliqué

Embroidery is the attaching of threads to an already formed piece of fabric. The technique has fewer restrictions as to where conductive elements can be placed as it is not bound to the grid or loop structures of woven and knit fabrics. The availability of consumer sewing machines and computer-controlled digital embroidery machines makes the technique accessible to those without textile training, which is likely one of the reasons it has been so frequently employed in e-textiles projects. McCann and Bryson (2009) is a recommended resources for a more in-depth review of the technique. Embroidery was the technique first used in the earliest audio projects, the MIDI Jacket and Musical Ball (Post et al., 2000), but continues to be used projects including (Karrer et al., 2011; Roh et al., 2011; Sicchio et al., 2016; Grant, 2017).

Appliqué is a related technique in that it is also is the application of a secondary material onto a base substrate, but instead of attaching a thread to fabric, is the attaching of another smaller piece of fabric to the first. It is often used in conjunction with embroidery as a decorative technique. However it is a popular method for constructing e-textiles as conductive fabrics often have more desired electrical properties than individual strands of conductive thread; lower electrical

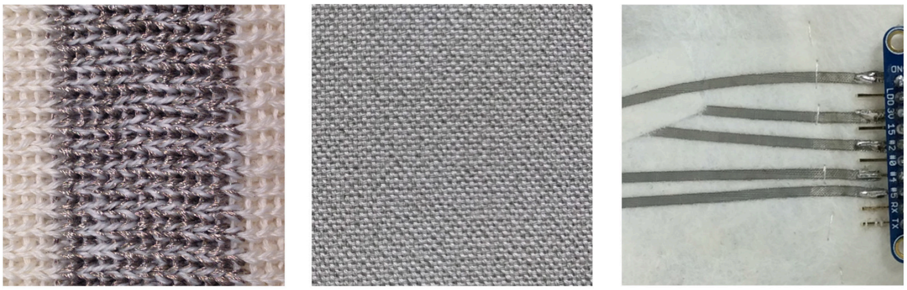

FIGURE 2 | Examples of the three textile fabrication techniques primarily used in e-texile construction: knitting, weaving, and embroidery or appliqué. **(Left)** Knit conductive stripe. **(Center)** Woven conductive fabric. **(Right)** Appliquéd conductive fabric.

impedance being the primary trait. Appliqué has been used in Sicchio et al. (2016), EJTECH (2017b), Satomi (2017), Wicaksono and Paradiso (2017), and Donneaud et al. (2017). A portion of the appliquéd circuitry from Sicchio et al. (2016) can be seen in **Figure 2** and an appliquéd speaker by EJTech can be seen in **Figure 2**. The combination of embroidery and appliqué techniques along with how they relate to each other is explored in the iterative development of the Stitched Sampler (Schoemann and Nitsche, 2017).

3.1.4. Printing

Printing is the least commonly found technique in audio applications using e-textiles, but it is not entirely absent. Printing involves laying down ink with suspended copper, silver, or carbon particles either through a silkscreen or inkjet process. Similar to embroidery, the placement of conductive material is not restricted to the textile structure. A conductive paste is often used to connect electrical components to the printed circuit. This process is used by Lee et al. (2010) to build a flexible MP3 player.

3.1.5. Encapsulation

An alternative to using conductive threads and fabrics to connect electrical components that are added to a textile structure is to work with extremely small electronics packages and directly embed components into a yarn (Rathnayake and Dias, 2015). That yarn is then knit or woven into a textile. This technique has been successful with components with two connections such as LEDs, thermistors and MEMs microphones (Hughes-Riley and Dias, 2018). A similar approach has recently been shown where materials are layered to form OLEDs directly on a fiber which is then woven or knit into a textile (Kwon et al., 2018).

3.2. Sensing Technologies

By far the most common role of e-textiles within computational audio projects is to sense physical movement and transform it into electrical signals which in turn control the generation of audio either on the same embedded device as the sensor or networked to a computer performing the audio computation.

This section reviews the most common sensing technologies employed where textiles are an essential part of the sensor. What is not included here—and is found in a minority of the e-textiles projects discussed—is acoustic sensing, which when used relies on MEMs or electret microphones that do not involve textiles in the sensing mechanism.

3.2.1. Detecting Contact of Conductive Surfaces

The most electrically simple sensor consists of two electrodes which close a circuit when they are in contact with each other. The physical design of the electrodes dictates the interaction that they capture. The most common arrangement is for two pieces of conductive fabric to be separated by a non-conductive spacer material. When pressure is applied, the two conductive fabric pieces are able to make electrical contact through holes in the spacer. This is how a fabric tactile pushbutton is constructed, which has the same affordances as a pushbutton made of metal and plastic, but can be flexible and directly integrated into textiles. The Keyboard by Post and Orth (1997), the assistive technology audio board by Profita (2012), the Musical Shoes (Grant, 2016), and Masai Dress by Despina Papadopoulos (Buechley et al., 2013) all use this sensor. However, it can be implemented with any pair of conductive surfaces including two pieces of fabric screen-printed with conductive ink (Lee et al., 2010).

The Music Sleeve (Gowrishankar et al., 2011) uses the closing of a circuit in a different configuration to control a music player. A knitted fabric tube or sleeve is worn around the body like a sash with sections knit with conductive thread. The continuous tube encloses a set of weighted conductive objects. When the sleeve is rotated around the wearer, gravity moves the weighted conductive objects to the lowest portion. The conductive objects then close the circuit between a pair of conductive fabric sections, indicating to a microcontroller the orientation of the sleeve.

The Sonic Quilt (Stark, 2017) uses the same electrical properties with an entirely different user interaction. A non-conductive piece of fabric separates two pieces of conductive fabric which each surround a magnet, causing the two conductive fabrics to be attracted to each other. The user pulls on a fringe of non-conductive fabric separating the conductive fabric sections, removing it and closing the switch.

3.2.2. Piezoresistivity

Piezoresistive sensors translate a physical movement such as strain or pressure into a change in electrical resistance. This sensing mechanism is one that can be implemented with textiles in a number of ways with the two primary methods being the compression of an electrically conductive foam or fabric to measure pressure or the stretching of conductive knit fabric to measure strain.

The material changing resistance under pressure starts with a higher resistance when no pressure is applied and then decreases resistance as the material is compressed. The material can be constructed from knitted conductive yarn (Kettley and Briggs-Goode, 2010) or felted conductive fibers (Grant, 2012).

Commercially available materials also exhibit this effect. Velostat and electrostatic discharge (ESD) foam are plastic packaging materials impregnated with carbon black. They were originally designed for protecting electronic circuitry in transit, but have found a second market in do-it-yourself sensor construction. Eeonyx also manufactures textiles coated with a conductive polymer that exhibits a piezoresistive effect when compressed.

Each individual key of the FabricKeyboard (Wicaksono and Paradiso, 2017) is a pressure sensor consisting of a sandwich of conductive fabrics and piezoresistive fabric produced by Eeonyx. The same configuration of fabrics is used in some of the musical interface experimentations explored by Freed (2008). Instead of piezoresistive fabric, Yoon et al. (2016) use a conductive polymer paint as the piezoresistive material in their sensor which measured pressure and strain. Grant (2012) constructed piezoresistive materials using felting techniques, distributing conductive fibers amongsts non-conductive fibers and generating a piezoresistive effect.

Knit structures with conductive yarns exhibit a piezoresistive effect. The properties of this effect come from a number of factors, but are all rooted in the path of the electricity being altered when the fabric is stretched. The loop structure provides multiple contact points whose resistance decreases as a strain is applied and pressure increased between the contacts (Atalay et al., 2013). The construction of the knit material is determined by the number of loops and how tight or loose they are in relation to each other. The structure of the loops in relation to each other is a function of the machine or hand tools used and accompanying design parameters. For example, the tightness of the loops in a fabric has been shown to effect the sensor performance, but similar performance can be found in both hand and machine knit textiles (Stewart and Skach, 2017) and less compact fabric has better accuracy when relaxed (Atalay et al., 2017). Stretch sensors can be made from the same commercial fabrics used in pressure sensing, but in a slightly different configuration and conductive yarns can also knit into bespoke shapes for a specific garment as was done for Aeolia (Glazzard and Kettley, 2010; Kettley and Briggs-Goode, 2010).

3.2.3. Capacitive Sensing

Capacitive sensing to detect touch or proximity is another popular sensing technique as it can be constructed using a variety of textile processes and is more tolerant of materials with higher impedances. It relies on the effect of a conductive antenna varying its capacity to hold a charge based on the distance of another object in the environment. See Wimmer (2011) for a concise overview of the technical details an limitations of using capacitive sensing for interacting with the body and (Baxter, 1997) for a more detailed technical explanation.

Capacitive sensing is particularly effective when combined with digital embroidery where a computer-controlled sewing machine can precisely place conductive threads on non-conductive fabric. This was the approach for both the Musical Jacket (Post et al., 2000) which played MIDI notes when the embroidered numberpad was touched and Aural Fabric (Milo and Reiss, 2017) which played binaural audio soundscapes that corresponded to the location touched on the embroidered map.

EJTECH is an experimental art and design research lab whose work has experimented with new materials largely for interactive sound installations. Much of there work has looked at how conductive materials from textiles to crystals can be used as capacitive sensors to control audio generation. One such example is SIMI, a stroke sensor that captures nuanced movements that in turn drives a synthesizer (EJTECH, 2017a, 2018).

3.2.4. Scaling and Combining Sensors

The three technologies described above can each provide a single, constrained channel of information about the physical state of an interface, but each have the ability to provide richer information when the number of sensors is greatly increased. The early research project Musical Balls (Weinberg et al., 2000) contained eight capacitive pressure sensors explicitly so that the channels could be manipulated concurrently and continously through single gestures.

Greatly increasing the number and density of contact sensors allows Pinstripe Karrer et al. (2011) to use the action of pinching and rolling a piece of fabric with one hand to control a music player. The underside of the fabric has rows of parallel conductive traces sewn with conductive thread which are used to detect how the textile has been deformed.

Musical hardware interfaces that capture two dimensions of gestural information have existed in many forms with the Korg Kaoss Pad being a significant influence. Similar controllers using e-textiles have been developed using both piezoresistive (Freed, 2009; Schmeder and Freed, 2010; Roh et al., 2011; Donneaud et al., 2017) and capacitive sensing (Post et al., 2000; Poupyrev et al., 2016) techniques. More sophisticated signal processing algorithms are needed to interpret nuanced interactions, and a combination of computer vision (Donneaud et al., 2017) and machine learning (Schmeder and Freed, 2010) approaches have proven effective.

Combining multiple sensing functionalities into a single set of conductive textile electrodes has been explored by Freed and Wessel (2015), but the FabricKeyboard (Wicaksono and Paradiso, 2017) is particularly noteworthy in that it combines all three sensor technologies into a single interface. It looks like a traditional piano keyboard made out of sewn fabrics. Keys generate a signal to play a sound only when enough pressure is applied to cause two conductive fabrics to come in contact with each other through a spacer mesh material. Once pressed the key acts as a continuous pressure controller due to the piezoresistive sandwich of fabrics in the key. Before a key is even touched, proximity of the hands of the player can be detected using capacitive sensing.

3.3. Actuating Technologies

While e-textiles are more commonly found as sensors or the inter-connections between components in a circuit, they can also perform as actuators. We will focus on two technologies in which textiles are core to their implementation and not focus on others which largely rely on non-textile components such as vibration motors.

The first technology is changing the color of a textile through the application of heat as a response to an aural stimulus or as a multi-modal reinforcement of the production of an audio signal. Fabrics or yarns dyed with thermochromic dyes change color when electrical current heats the underlying conductive yarn. Berzowska and Bromley (2007) were two of the pioneers of this technique, though did not use computational audio in their work. Experimental art and design lab EJTECH have combined the techniques they developed with audio signals in their project Chromosonic to create a textile that changes colors due to the audio signals passing through resistive wires causing the textile to heat up (EJTECH, 2014).

The second actuation technique found within computational audio e-textiles is using conductive threads or fabrics to act as loudspeaker voice coils. A fixed magnet is attached to a textile embroidered or appliquéd with a spiral of conductive thread or fabric. The alternating current of the audio signal passing through the conductive thread or fabric causes the fabric it is attached to to be attracted to or repelled from the fixed magnet, turning the textile into an acoustic transducer. This effect was first demonstrated using embroidery with the Accouphène project by XS Labs (Seymour, 2008), and has been explored in many projects since with the Crying Dress (Perner-Wilson and Satomi, 2012) and Sonic Quilt (Stark, 2017) being notable examples.

EJTECH have conducted a series of design experiments exploring bonded appliquéd textile speakers in a project called SOFT SOUND (EJTECH, 2017b, 2018). Difficulties of working with textile speakers include trying to balance the magnetic field surrounding a fixed magnet with the size of the conductive textile coil and determining which textiles perform best as substrates. For instance, they have found that nine tight coil turns of conductive thread produces around 16Ω which when paired with a 5cm diameter neodymium magnet results in a stable loudspeaker. In parallel, they have found that particular configurations are best suited for narrow-band audio playback with broader audio ranges more accurately represented across multiple speakers with differing combinations of weight of textile substrate and coil turns. They have also combined their textile speaker work with thermochromics so that they can control the color change of a screen-printed textile substrate according to the sound being sent to the speaker. One of their appliquéd speakers can be seen in **Figure 3**.

4. APPLICATIONS AREAS

The above section surveyed the technologies used within e-textiles developed for computational audio, this section will look at the application areas where e-textiles are repeatedly being employed for audio-related tasks. There are five primary themes that emerge from the projects surveyed: educational projects for teaching electronics or coding; malleable objects as human-computer interfaces; audio-driven interfaces for data sonification; assistive technology devices; and wearable interfaces.

FIGURE 3 | Textile speaker (EJTECH, 2017b). Photo provided by EJTECH.

4.1. Education

E-textiles have a history rooted in school and higher education, particularly with the LilyPad which was initially tested with 10–14 year olds in workshop settings. Conductive threads and fabrics have since been identified as materials that can attract underrepresented groups such as girls and women to coding and electronics (Buechley and Hill, 2010; Buechley et al., 2013; Buchholz et al., 2014; Weibert et al., 2014).

Buechley et al. (2013) provide an excellent overview of the work done to create educational lessons and toolkits using e-textiles. Many of the first lessons center around LEDs as the primary actuator in circuits. Pedagogically this is a natural fit as it is relatively simple to explain the surrounding circuitry for an LED and it can quickly demonstrate the interactivity of sensors and microcontrollers.

Audio is frequently the second actuation modality to be taught (with motors and other haptics following). Examples include the i*CATch kit (Ngai et al., 2010) which uses sound elements including microphones and speakers as available building blocks for constructing interactive embedded projects. Another resource is a book of e-textile projects by Blumenkratz (2017) designed for ages 10 and older for creating Arduino-based synthesiser t-shirts and interactive sound-generating tote bags which focuses on the hand-crafting of contact switches and piezoresistive senors. Examples aimed at learners outside of school include the Solo Disco Scarf (Codasign, 2013), an educational project that teaches basic analog audio signal processing through the sewing of a wearable stereo-to-mono mixing and panning circuit .

While the majority of educational projects involving e-textiles aim to teach technical skills to those drawn to crafting with textiles, Schoemann and Nitsche (2017) used e-textiles to develop educational aids for apprentice seamstresses practicing hand-stitching techniques. They used audio as a feedback mechanism for the needle passing through the fabric.

4.2. Malleable Objects

The majority of the projects surveyed are wearable interfaces, with the remaining ones being objects that are interacted with but not worn. Many of these researchers chose to implement their design with e-textiles because the interfaces are designed to be deformed as means to generate data. The earliest such example, a fabric keyboard, was descried by its creators as "satisfying to make music by crushing and crumpling" (Post et al., 2000). The Embroidered Musical Ball (Weinberg et al., 2000) from the same research lab had eight continuous pressure sensors mapped to musical parameters which were manipulated through squeezing the object and this tactility of audio parameters was also used in the felt sensors by Grant (2012). Topley (Bowers et al., 2016) scaled up the Embroidered Musical Ball project to create an 80cm diameter knit sphere named "ball." Instead of using e-textile sensors, it embedded accelerometers in the middle of the object whose data drove a wirelessly-connected audio synthesis engine. The size and materials were intentionally chosen to encourage engagement between performances and audience in a performance context.

Chang and Ishii (2007) directly reference the malleability of textiles in their design of their audio controller Zstretch, though their final design was fabric stretched and mounted in a frame as opposed to a completely unrestricted piece of fabric. They observed that the "topological constraints" of the material meant that individual parameters could not be isolated when interacting with the object, but they found this to be beneficial to creative expression. These interactions would not be possible with rigid materials and rely on the plasticity of textiles. Another example being s-Bojagi by O'Nascimento (2011), a patchwork blanket with integrated e-textile sensors that are used to control audio synthesis when the blanket is wrapped around objects.

The malleability of an object also serves a utilitarian purpose for some researchers. Nakad et al. (2007) chose to build a beamforming array on a textile substrate as the flexibility of the material was viewed as a strength as it could withstand repeated movements. As their array was over 90 square feet, the portability of such a large object must have been a factor as well, though was not explicitly discussed.

Textiles can facilitate further tactile interactions beyond deformations, with soft, pleasing to touch fabrics being a driving factor in physical interfaces. Donneaud et al. (2017) acknowledge that textiles were chosen for their pressure pad interface not only for their affordances but the aesthetics offered by the material. This is echoed in the FabricKeyboard (Wicaksono and Paradiso, 2017) whose flexibility and rich set of sensors allows it to capture interactions and encourages the explorations of the musical effects of stretching, squishing, and generally deforming the object. Barrass (2008) explored this with ZiZi the Affectionate Couch, a couch upolstered in touch sensitive faux fur. The fur invited a stroking motion detected by embedded sensors which then generated an audible "purring" in response.

4.3. Sonification

Sonification is the transformation of non-audio data streams into aural information, whether air quality (Arrango and Arango, 2017), electromagnetic fields (Psarra, 2017), or movement data (Lamb, 2017). All three data streams have been embedded into wearable audio systems that sonify the data in real-time for the wearer: the AirQ Jacket (Arrango and Arango, 2017); Fractal Kimono (Psarra, 2017); Cyberknitics sleeve and holster (Lamb, 2017).

Instead of creating a wearable interface for playback of data, the Aural Fabric by Milo and Reiss (2017) uses e-textiles as a tactile interface. It is a digitally embroidered, touch-sensitive map that when the user touches a location on the map, they hear a binaural soundscape recorded at that location.

4.4. Assistive Technology

E-textiles provide a tactile and wearable interface that allows for interactions that do not center around a screen. This makes them an ideal partner for audio-haptic interfaces for the blind and visually impaired community. Wiseman et al. (2015) created a tablecloth for visually impaired theatre goers for capturing survey information. Zippers at each place setting on the tablecloth could be zipped up or down to indicate a scaled response with haptic feedback provided by the zippers reinforced with aural feedback. Giles and van der Linden (2015) worked with similar communities, using handwoven e-textiles with capacitive sensing to cultivate community and memory through audio-haptic objects.

Wearable sensory substitution assistive technology has also been developed for visually impaired communities. The Flutter Dress (Profita et al., 2015) listens for directional audio and then triggers haptic responses through vibration motors to indicate to the wearer the presence and direction of a sound source. The Proximity Hat (Berning et al., 2015) has a similar concept to the Flutter Dress, but it uses ultrasonic sensors to detect physical obstacles and relays that directional information into vibration motors.

E-textiles interfaces using computational audio can be found in interfaces for other communities beyond the visually impaired. Grant (2017) worked with a group of students to develop prototypes to assist those with Cerebral Palsy—work that has since contributed to the FlexAbility project (Blumenkratz et al., 2018). Sensory-rich spaces are used in therapeutic contexts for a variety of communities with special needs and was the focus of the RHYME Project (Cappelen and Andersson, 2016). They developed a series of soft objects and play structures with embedded sensors that affected emitted lights and sounds. Other interfaces have centered around audio as the sole output with a glove triggering audio files of spoken words and a wearable triggering sounds through a selection of movement. Profita (2012) found the affordances of textiles to be particularly useful for building a wearable speech board for autistic horseback riders.

4.5. Wearable Interfaces

The majority of the surveyed computational audio projects using e-textiles were wearable interfaces. This is unsurprising given that textiles are quickly associated with clothing. As such, they are natural ways for capturing information generated by the body, relaying information to the wearer, or providing a convenient interface that does not require holding an object. The two themes that arose the most often were wearable music players and wearable computing systems for creative expression within the performing arts.

4.5.1. Portable Music Players

The most prevalent application of audio interfaces using e-textiles is to control an MP3 player, which is also a useful demonstrating application for audio-only interface tasks such as navigating menu structures. The early 2000s saw the "MP3 Jacket Craze" when numerous apparel and technology companies tried integrating MP3 playback into the sleeves of garments such as snowboarding jackets (Seymour, 2008; McCann and Bryson, 2009). The ability to control a music player via your clothing remains a commercial interest even today. Google and Levi's collaborative denim Commuter Trucker Jacket that can recognize gestures and communicate with a smart phone features its ability to control a music playlist in the online video advertising the product (Levi's, 2016).

Wearable portable music players serve as a common demonstrator for interaction design with textile interfaces. Researchers have used it as use-case for exploring interactions for a wearable music player by asking users to describe potential interaction through a "Wizard-of-Oz" study (Kim et al., 2010). Others have tested novel interfaces such as pinching and rolling fabric (Karrer et al., 2011), rotating a worn knit tube of fabric around the body (Gowrishankar et al., 2011), and the pressing of the thumb against the index finger to navigate a playlist (Yoon et al., 2016). This application area has also been used as a demonstrator for new e-textile fabrication techniques such as printing with conductive ink (Lee et al., 2010).

4.5.2. Performing Arts

The performing arts—particularly music and dance—have a long history with wearable interfaces. Wearable sensors worn by dancers to directly generate audio can be seen as early as 1989 in MidiDancer by Mark Coniglio of Troika Ranch (Dixon, 2007, Chapter 1). While e-textiles were not used, flex sensors measured the angles of the dancers' joints and converted their values to MIDI data which was transmitted wirelessly to a computer to control the manipulation of video files. Wearable interfaces for capturing body movement for performing arts have since proliferated as e-textiles have become a more accessible fabrication technique for artists, designers, and musicians.

Systems where the dancer acts also as the sound generator or instrument include: Parangonet 1.0 - Sonic Dimension by Jader Scalzaretto and O'Nascimento (2011); The Space Between Us (Buechley et al., 2013); Idoru() (Psarra, 2013); Soft Articulations (Psarra, 2014); Flutter/Stutter (Sicchio et al., 2016); Musical Shoes (Grant, 2016); and Amateur (Dubrule et al., 2016).

Other performance settings include Rambu (Satomi, 2017), performed calligraphy, and where dancing is gamified and captured through sensors integrated into socks (Yang et al., 2011).

While it is not always easy to classify a performer as a dancer vs. a musician, there are several interfaces explicitly designed to capture the movements made by musicians and to alter the musical performance. Aeolia (Kettley and Briggs-Goode, 2010) is a wearable e-textile sensor for a cellist which was the result of textile materials and construction experimentations and body:suit:score is a garment developed for communicating score information to a solo performing musician (Bhagwati et al., 2016). There have been commercial products within this area brought to market, the first being the MIDI Jacket by Machina (2018) which captures body movement and control signals like the zipping of zippers and the second being mi.mu Gloves (MI.MU Gloves Limited, 2018) which classify hand postures through bend sensors over each finger. Both the MIDI Jacket and mi.mu Gloves are targeted at electronic music producer and performers who wish to interact with and control their music through embodied gestures.

5. DISCUSSION

E-textiles, particularly within fashion contexts, can too easily be dismissively viewed as lights embedded in garments, without considering other actuation modalities. However, a greater range of interactions and applications are available. E-textiles have incorporated computational audio since the first publications in the field, but there were limitations when the field was in its infancy. Those who had access to this emerging technology were largely within academic research labs; those wanting to work with e-textiles needed a strong foundation in electrical engineering. Initial work was concentrated toward military applications, with only a small selection of researchers investigating artistic uses. While e-textiles research is still being applied to defense applications today, it has also been heartily adopted by designers and engineers looking at more creative domains. This can be credited to the lowering of hardware costs and the reduction of learning curves for working with embedded systems.

The Arduino microcontroller platform and the LilyPad in particular made developing embedded technology much more accessible to a wider range of communities. Artists, fashion designers, and assistive technology designers all started creating bespoke interfaces to fulfill niche requirements. Both a growing body of research publications and online resources such as Kobakant's *How to Get What You Want* (Kobakant, 2018a) have allowed a collection of best practices to develop and facilitate innovations that build on the accomplishments of the work that came before. These best practices include a collection of tested sensor technologies that can capture a variety of interactions, whether on the body or in a separate object. E-textile actuator technologies are more nascent, but have caught the interest of artists and designers along with material scientists and mechanical engineers who are working to build up shared knowledge.

5.1. E-Textiles for a Material Turn

Alongside developing technical best practices for building sensor and actuator systems, e-textiles research is currently situating itself within the larger human-computer interaction research field. The emerging importance of materiality within interaction design and the "material turn" of the field (Robles and Wiberg, 2010; Wiberg, 2017) creates an opportunity for textiles to play an even greater part in future interactions. This will necessitate the interdisciplinary cooperation from a spectrum of skills, especially for computational audio applications. A range of expertise will be required in order to properly engage with textile, audio, and interaction design (Tomico and Wilde, 2016).

When placing these interactions on the body, the human-garment interaction design requires even more skillsets to be considered (McCann and Bryson, 2009, Chapter 5). Knowledge from fashion about how to dress the body will be essential (Joseph et al., 2017), and it is already making contributions in advising which sensor technologies should be placed where according to their affordances (Zeagler, 2017).

5.2. Sophistication and Nuance

When looking back over wearable interfaces within domains like dance, the same embedded system architecture used in MidiDancer in the 1980s can still be seen in use today (Dixon, 2007, Chapter 1). The data captured on the body is wirelessly sent to another computer to generate audio. This effectively tethers the user to an object that is not the e-textile interface. As processing power increases on embedded devices, more advanced interpretation of the data will be calculated on the body or embedded within an object. Ideally it will be able to solve a greater variety of problems such as those addressed by assistive technology, by implementing more cutting-edge algorithms than have been found in previous work to date.

As wearable e-textile interfaces become more ubiquitous, the research community is ready to move past simplistic mappings between sensor values and sounds and on to more nuanced interactions. This needs to come from increasing the density of sensors on the body or interactive object and simultaneously from utilizing more sophisticated signal processing algorithms in order to interpret the data in real time. Work has begun on applying computer vision (Donneaud et al., 2017) and machine learning Poupyrev et al. (2016) algorithms to e-textile sensor data, particularly with regards to two-dimensional trackpad-like interfaces. Once supporting software libraries are available to interaction designers which can then be easily incorporated into interactive prototypes, the results will be transformative.

5.3. Looking Forward

Manufacturing e-textiles at scale still remains a problem with industrial engineering issues such as fabrication and connections between inflexible and flexible conductive materials not yet fully solved. Google's Project Jacquard is an important turning point as it is a major technology company investing significant funds into research that recognizes the potential of e-textile interfaces. Though their first product does not appear far removed from the "MP3 Jacket Craze" of the early 2000s, the technical research and development underpinning the product may still prove to be revolutionary.

Attempting to predict the future potential of a technology is seldom a worthwhile venture, but what is certain is that computational audio will continue to play a vital role in e-textile development. As hardware and software tools for e-textiles mature and become easier to access, those within computing disciplines will be able to work with textile interfaces even if they have limited textile construction experience, and designers will be able to implement more nuanced interactions by using advanced algorithmic tools. As has already been demonstrated with e-textiles and computational audio, true innovation will require advanced knowledge from multiple domains collaborating together.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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REFERENCES

Ambience (2011). *Ambience 11*. Available online at: http://www.ambience11.se/

ArcInTex (2018). *ArcInTex Network*. Available online at: http://arcintex.hb.se/

Arrango, M. P. G., and Arango, J. J. (2017). "Design process for wearable technologies and urban ecology, AirQ Jacket," in *Proceedings of the 23rd International Symposium on Electronic Art (ISEA) 2017* (Manizales), 443–452.

Atalay, O., Kennon, W. R., and Husain, M. D. (2013). Textile-based weft knitted strain sensors: effect of fabric parameters on sensor properties. *Sensors* 13, 11114–11127. doi: 10.3390/s130811114

Atalay, O., Tuncay, A., Husain, M. D., and Kennon, W. R. (2017). Comparative study of the weft-knitted strain sensors. *J. Indus. Tex.* 46, 1212–1240. doi: 10.1177/1528083715619948

Barrass, S. (2008). Clothing the Homunculus : interactive tactile textile interface clothing the homunculus. *Vis. Commun.* 7, 317–329. doi: 10.1177/1470357208092322

Baxter, L. K. (1997). "Capacitive sensor basics," in *Capacitive Sensors: Design and Applications* (Wiley-IEEE Press), 37–47.

Berning, M., Braun, F., Riedel, T., and Beigl, M. (2015). "ProximityHat," in *Proceedings of the 2015 ACM International Symposium on Wearable Computers - ISWC '15* (Maui, HI), 31–38. doi: 10.1145/2802083.2802088

Berzowska, J., and Bromley, M. (2007). "Soft computation through conductive textiles," in *Proceedings of the International Foundation of Fashion Technology Institutes Conference* (Toronto, ON), 1–12.

Bhagwati, S., Giordano, M., Berzowska, J., Bachmayr, A., Stein, J., Browne, J., et al. (2016). "Musicking the body electric. The 'body:Suit:Score' as a polyvalent score interface for situational scores," in *Proceedings of the International Conference on Technologies for Music Notation and Representation* (Cambridge), 121–126.

Blumenkratz, A. (2017). *Wearables für Maker*. Franzis.

Blumenkratz, A., Grant, L., and Freed, A. (2018). *FlexAbility*. Available online at: http://flex-ability.org/.

Bowers, J., Richards, J., Freeth, B., Shaw, T., Frieze, J., Topley, S., et al. (2016). "One knob to rule them all: reductionist interfaces for expansionist research," in *Proceedings of the International Conference on New Interfaces for Musical Expression* (Queensland, QL), 433–438.

Buchholz, B., Shively, K., Peppler, K., and Wohlwend, K. (2014). Hands on, hands off: gendered access in crafting and electronics practices. *Mind Cult. Act.* 21, 278–297. doi: 10.1080/10749039.2014.939762

Buechley, L., Eisenberg, M., Catchen, J. and Crockett, A. (2008). "The LilyPad Arduino: using computational textiles to investigate engagement, aesthetics, and diversity in computer science education," in *Proceeding of the Twenty-Sixth Annual SIGCHI Conference on Human Factors in Computing Systems (CHI)* (Florence), 423–432. doi: 10.1145/1357054.1357123

Buechley, L. and Hill, B. M. (2010). "LilyPad in the wild: how hardware's long tail is supporting new engineering and design communities," in *Proceedings of ACM DIS 2010* (Aarhus), 199–207. doi: 10.1145/1858171.1858206

Buechley, L., Peppler, K., Eisenberg, M., and Yasmin, K. (eds.). (2013). *Textile Messages: Dispatches from the World of E-Textiles and Education. New Literacies and Digital Epistemologies*. Peter Lang Publishing Group.

Cappelen, B., and Andersson, A.-P. (2016). "Health improving multi-sensorial and musical environments," in *Proceedings of the Audio Mostly 2016 on - AM '16* (Norrköping), 178–185. doi: 10.1145/2986416.2986427

Chang, A., and Ishii, H. (2007). "Zstretch: a stretchy fabric music controller," in *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)* (New York, NY), 46–49. doi: 10.1145/1279740.1279746

Codasign (2013). *Solo Disco Scarf Tutorial*. Available online at: http://www.codasign.com/events/solo-disco-scarf/

Dias, T., and Ratnayake, A. (2015). "Integration of micro-electronics with yarns for smart textiles," in *Electronic Textiles*, ed T. Dias (Woodhead Publishing), 109–116. doi: 10.1016/B978-0-08-100201-8.00006-0

Dixon, S. (2007). "Digital dancing and software developments," in *Digital Performance: A History of New Media in Theater, Dance, Performance Art, and Installation* (MIT Press), 183–208.

Donneaud, M., Honnet, C., and Strohmeier, P. (2017). "Designing a multi-touch eTextile for music performances," in *Proceeedings of New Interfaces for Musical Expression* (Copenhagen), 7–12.

Dubrule, D., Klitsner, S., and Brannum, B. (2016). *Amateur*. Available online at: http://www.dorothydubrule.com/AMATEUR

EJTECH (2014). *Chromosonic*. Available online at: https://vimeo.com/91989013

EJTECH (2017a). *Simi Stroke Sensor // NWoV Version*. Available online at: https://vimeo.com/205792057

EJTECH (2017b). *Soft Sound for TechTextil - Sounding Textile Series*. Available online at: https://vimeo.com/178484962

EJTECH (2018). *Email Correspondence*.

eTextile Summer Camp (2018). *eTextile Summer Camps*. Available online at: http://etextile-summercamp.org/

Freed, A. (2008). "Application of new fiber and malleable materials for agile development of augmented instruments and controllers," in *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)* (Genova), 107–112.

Freed, A. (2009). "Novel and forgotten current-steering techniques for resistive multitouch, duotouch, and polytouch position sensing with pressure," in *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)* (Pittsburgh, PA), 230–235.

Freed, A., and Wessel, D. (2015). "An accessible platform for exploring haptic interactions with co-located capacitive and piezoresistive sensors," in *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '14* (Munich), 317–320. doi: 10.1145/2677199.2680571

Giles, E., and van der Linden, J. (2015). "Imagining future technologies: ETextile weaving workshops with blind and visually impaired people," in *Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition* (Seoul), 3–12. doi: 10.1145/2757226.2757247

Glazzard, M., and Kettley, S. (2010). "Knitted stretch sensors for sound output," in *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '10* (Cambridge, MA), 391–392. doi: 10.1145/1709886.1709994

Gopalsamy, C., Park, S., Rajamanickam, R., and Jayaraman, S. (1999). The wearable motherboard^{TM}: The first generation of adaptive and responsive textile structures (ARTS) for medical applications. *Virt. Real.* 4, 152–168.

Gowrishankar, R., Bredies, K., and Chow, R. (2011). "The music sleeve: fabric as an electronic interface medium," in *Nordic Design Research Conference* (Helsinki), 1–6.

Grant, L. (2012). *Felt Sensors*. Available online at: http://lara-grant.com/portfolio/felt-sensors/

Grant, L. (2016). *Musical Shoes*. Available online at: http://www.instructables.com/id/Musical-Sneakers/

Grant, L. (2017). *Heirloom Electronic Jacket*. Available online at: http://lara-grant.com/portfolio/heirloom-electronic-jacket/

Heffer, C. (2007). 2007 *Reskin: Future of Wearable Technology*. Available online at: http://www.ceciliaheffer.com/lacenarratives-1/

Heinzel, T. (2014). "Haptic and sound correlations in textiles. in *Ambience '14* (Tampere), 7–9.

Hughes-Riley, T., and Dias, T. (2018). Developing an acoustic sensing yarn for health surveillance in a military setting. *Sensors* 18:E1590. doi: 10.3390/s18051590

Joseph, F., Smitheram, M., Cleveland, D., Stephen, C., and Fisher, H. (2017). Digital materiality, embodied practices and fashionable interactions in the design of soft wearable technologies. *Int. J. Design* 11, 7–15. Available online at: http://ijdesign.org/index.php/IJDesign/article/view/2845/791

Karrer, T., Wittenhagen, M., Lichtschlag, L., Heller, F., and Borchers, J. (2010). "Pinstripe: eyes-free continuous input on interactive clothing," in *Proceedings of UIST '10* (New York, NY), 1313–1322.

Karrer, T., Wittenhagen, M., Lichtschlag, L., Heller, F., and Borchers, J. (2011). "Pinstripe: eyes-free continuous input on interactive clothing," in *Proceedings of the 2011 Annual Conference on Human Factors in Computing Systems - CHI '11* (Vancouver, BC), 1313–1322. doi: 10.1145/1978942.1979137

Kettley, S. (2016). *Designing with Smart Textiles*. Fairchild Books.

Kettley, S., and Briggs-Goode, A. (2010). Aeolia: textile enquiry and design. *Duck J. Tex. Res. Tex. Des.* 1, 1–6. Available online at: http://irep.ntu.ac.uk/id/eprint/9348

Kim, K., Joo, D., and Lee, K-P. (2010). "Wearable-object-based interaction for a mobile audio device," in *Proceedings of CHI '10 Extended Abstracts on Human Factors in Computing Systems* (Atlanta, GA), 3865–3870. doi: 10.1145/1753846.1754070

Kobakant (2018a). *How to Get What You Want*. Available online at: https://www.kobakant.at/DIY/

Kobakant (2018b). *KOBA*. Available online at: https://www.kobakant.at/KOBA/

Kwon, S., Kim, H., Choi, S., Jeong, E. G., Kim, D., Lee, S., et al. (2018). Weavable and highly efficient organic light-emitting fibers for wearable electronics: a scalable, low-temperature process. *Nano Lett.* 18, 347–356. doi: 10.1021/acs.nanolett.7b04204

Lamb, T. (2017). *Cyberknitics*. Available online at: http://teresaflourlamb.com/cyberknitics.html

Lee, S., Kim, B., Roh, T., Hong, S., and Yoo, H. J. (2010). "Arm-band type textile-MP3 player with multi-layer planar fashionable circuit board (P-FCB) techniques," in *Proceedings - International Symposium on Wearable Computers, ISWC* (Seoul). doi: 10.1109/ISWC.2010.5665879

Levi's (2016). *Levi's® Commuter^{TM}x Jacquard by Google Trucker Jacket*. Available online at: https://www.youtube.com/watch?v=yJ-lcdMfziw

Machina (2018). *MIDI Jacket*. Available online at: https://www.machina.cc/

Marculescu, D., Marculescu, R., Zamora, N. H., Stanley-Marbell, P., Khosla, P. K., Park, S., et al. (2003). Electronic textiles: a platform for pervasive computing. *Proc. IEEE* 91, 1995–2016. doi: 10.1109/JPROC.2003.819612

McCann, J., and Bryson, D. (eds.). (2009). *Smart Clothes and Wearable Technology*. Woodhead Publishing.

METABODY (2018). *METABODY Project*. Available online at: http://metabody.eu/

MI.MU Gloves Limited (2018). *mi.mu Gloves*. Available online at: https://mimugloves.com/

Milo, A. and Reiss, J. D. (2017). Aural Fabric : an interactive textile sonic map. in *Proceedings of the 12th International Audio Mostly Conference on Augmented and Participatory Sound and Music Experiences* (London), 37:1–37:5. doi: 10.1145/3123514.3123565

Nakad, Z., Jones, M., Martin, T., and Shenoy, R. (2007). Using electronic textiles to implement an acoustic beamforming array: a case study. *Pervas. Mobile Comput.* 3, 581–606. doi: 10.1016/j.pmcj.2007.02.003

Ngai, G., Chan, S. C. F., Ng, V. T. Y, Cheung, J. C. Y., Choy, S. S.S., Lau, W. W. Y., et al. (2010). "I*CATch: a scalable, plug-n-play wearable computing framework for novices and children," in *Proceedings of the 28th International Conference on Human Factors in Computing Systems - CHI '10* (Atlanta, GA), 443–452. doi: 10.1145/1753326.1753393

O'Nascimento, R. (2011). *Parangonet 1.0 - Sonic Dimension*. Available online at: http://www.onascimento.com/#/parangonet-10-sonic-dimension/

Perner-Wilson, H., and Satomi, M. (2012). *The Crying Dress*. Available online at: http://www.kobakant.at/?p=222

Post, E. R., and Orth, M. (1997). "Smart fabric, or washable computing," in *Digest of Papers. First International Symposium on Wearable Computers* (Cambridge, MA), 167–168. doi: 10.1109/ISWC.1997.629937

Post, E. R., Orth, M., Russo, P. R., and Gershenfeld, N. (2000). E-broidery: Design and fabrication of textile-based computing. *IBM Syst. J.* 39, 840–860. doi: 10.1147/sj.393.0840

Poupyrev, I., Gong, N-W., Fukuhara, S., Karagozler, M. E., Schwesig, C., and Robinson, K. E. (2016). "Project Jacquard," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16* (San Jose, CA), 4216–4227. doi: 10.1145/2858036.2858176

Profita, H. P. (2012). "An electronic-textile wearable communication board for individuals with autism engaged in horse therapy," in *Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility* (Boulder, CO), 231–232. doi: 10.1145/2384916.2384968

Profita, H. P., Farrow, N., and Correll, N. (2015). "Flutter: an exploration of an assistive garment using distributed sensing, computation and actuation," in *TEI 2015 - Proceedings of the 9th International Conference on Tangible, Embedded, and Embodied Interaction*, 359–362.

Psarra, A. (2013). *Idoru()*. Available online at: http://afroditipsarra.com/index.php?/on-going/idoru/

Psarra, A. (2014). *Soft^Articulations*. Available online at: http://afroditipsarra.com/index.php?/on-going/softarticulations/

Psarra, A. (2017). Psarra, A. (2017). *Fractal Kimono*. Available online at: http://afroditipsarra.com/index.php?/on-going/fractal-antennae/

Qu, H., and Skorobogatiy, M. (2015). "Conductive polymer yarns for electronic textiles," in *Electronic Textiles*, ed T. Dias (Elsevier), 21–53. doi: 10.1016/B978-0-08-100201-8.00003-5

Quinn, B. (2013). *Textile Visionaries: Innovation and Sustainability in Textile Design*. Laurence King Publishing.

Rathnayake, A. and Dias, T. (2015). "Yarns with embedded electronics," in *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers - UbiComp '15* (New York, NY), 385–388. doi: 10.1145/2800835.2800919

Robles, E., and Wiberg, M. (2010). "Texturing the 'material turn' in interaction design," in *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '10* (Cambridge, MA), 137–144. doi: 10.1145/1709886.1709911

Roh, J.-S. Mann, Y., Freed, A., and Wessel, D. (2011). "Robust and reliable fabric and piezoresistive multitouch sensing surfaces for musical controllers," in *Proceedings of the International Conference on New Interfaces for Musical Expression* (Oslo), 393–398.

Ryan, S. E. (2014). *Garments of Paradise: Wearable Discourse in the Digital Age*. MIT Press.

Satomi, M. (2017). *Rambu*. Available online at: http://www.nerding.at/rambu/

Satomi, M., and Perner-Wilson, H. (2011). "Future master craftsmanship: where we want electronic textile crafts to go," in *The 17th International Symposium on Electronic Art ISEA 2011* (Istanbul), 1–8.

Schmeder, A., and Freed, A. (2010). "Support vector machine learning for gesture signal estimation with a piezo-resistive fabric touch surface," in *Proceedings of the 2010 Conference on New Interfaces for Musical Expression (NIME 2010)* (Sydney, NSW), 244–249.

Schoemann, S., and Nitsche, M. (2017). "Needle as input: exploring practice and materiality when crafting becomes computing," in *Proceedings of the Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '17* (Yokohama), 299–308. doi: 10.1145/3024969.3024999

Seymour, S. (2008). *Fashionable Technology: The Intersection of Design, Fashion, Science, and Technology*. Springer Verlag.

Sicchio, K., Baker, C., Mooney, T. B., and Stewart, R. (2016). "Hacking the body 2.0?: flutter/stutter," in *Proceedings of the International Conference on Live Interfaces (ICLI '16)* (Brighton), 37–42.

Stark, L. (2017). *Sonic Quilt: Fringes*. Available online at: http://thesoftcircuiteer.net/projects/sonic-quilt-fringes/

STEIM (2015a). *E-Textile Project*. Available online at: http://steim.org/2015/06/e-textile-aftermovie/

STEIM (2015b). *Embroidered Bits*. Available online at: http://steim.org/event/embroidered-bits/

STEIM (2015c). *Sounding Textiles*. Available online at: http://steim.org/event/sounding-textiles/

Stewart, R., and Skach, S. (2017). "Initial investigations into characterizing DIY E-textile stretch sensors," in *Proceedings of the 4th International Conference on Movement Computing, MOCO '17* (London), 1–4. doi: 10.1145/3077981.3078043

Stoppa, M., and Chiolerio, A. (2014). Wearable electronics and smart textiles: a critical review. *Sensors* 14, 11957–11992. doi: 10.3390/s140711957

Tomico, O., and Wilde, D. (2016). Soft, embodied, situated & connected: enriching interactions with soft wearables. *MUX: J. Mobile User Exp.* 5. doi: 10.1186/s13678-016-0006-z

Weibert, A., Marshall, A., Aal, K., Schubert, K., and Rode, J. (2014). "Sewing interest in e-textiles: analyzing making from a gendered perspective," in *Proceedings of the 2014 Conference on Designing Interactive Systems - DIS '14* (Vancouver, BC), 15–24. doi: 10.1145/2598510.2600886

Weinberg, G., Orth, M., and Russo, P. (2000). "The embroidered musical ball: a squeezable instrument for expressive performance," in *Proceedings of the 2000 CHI Conference on Human Factors in Computing Systems - CHI 2000* (The Hague), 283–284. doi: 10.1145/633292.633457

Wiberg, M. (2017). *The Materiality of Interaction: Notes on the Materials of Interaction Design*. MIT Press.

Wicaksono, I., and Paradiso, J. A. (2017). "FabricKeyboard?: multimodal textile sensate media as an expressive and deformable musical interface," in *Proceedings of the International Conference on New Interfaces for Musical Expression* (Copenhagen), 348–353.

Wimmer, R. (2011). "Capacitive sensors for whole body interaction," in *Whole Body Interaction*, ed D. England (Springer Verlag), 121–33. doi: 10.1007/978-0-85729-433-3

Wiseman, S., Van Der, J., Spiers, A., and Oshodi, M. (2015). "An interactive tablecloth for facilitating discussion in a culturally diverse group," in *Proceedings of Cultural Diversity and Technology Design Workshop at 7th International Communities and Technologies Conference* (Limerick).

Yang, C. M., Hu, J. S., Yang, C. W., Wu, C. C., and Chu, N. (2011). "Dancing game by digital textile sensor, accelerometer and gyroscope," in *2011 IEEE International Games Innovation Conference, IGIC 2011* (Orange City, CA), 121–123. doi: 10.1109/IGIC.2011.6115112

Yoon, S. H., Huo, K., and Ramani, K. (2016). Wearable textile input device with multimodal sensing for eyes-free mobile interaction during daily activities. *Pervas. Mobile Comput.* 33, 17–31. doi: 10.1016/j.pmcj.2016.04.008

Zeagler, C. (2017). "Where to wear it: functional, technical, and social considerations in on-body location for wearable technology 20 years of designing for wearability," in *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (Maui, HI), 150–157. doi: 10.1145/3123021.3123042

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