Exploration of interdisciplinary approaches to improve the wearability of next to skin e-textile applications

Finn Godbolt[1*], Daniel Collings[2*], Andrew Lowry[3], Jyoti Kalyanji [4], and Andrew Lowe[5]

Auckland University of Technology [1]finn.godbolt@aut.ac.nz, [2] dan.collings@aut.ac.nz, [3]andrew.lowry@aut.ac.nz, [4]jyoti.kalyanji@aut.ac.nz, [5]andrew.lowe@aut.ac.nz
***Corresponding and presenting authors**

ABSTRACT

This paper shares findings from a discovery phase in an ongoing interdisciplinary e-textiles project aimed at developing wearable e-textile connectors. An inquiry into the design criteria of connectors prompted a broader review of e-textile wearability in general. E-textile literature, particularly for next-to-skin applications, highlights its positioning in engineering disciplines, with value placed on novel electronic componentry and conductive materials or advances in methods for sensing or responding.

Discussion on wearability is often limited to the integration of electronic components within the textile or narrow definitions of comfort, focused on breathability and washability. Additionally, design considerations are primarily directed at ensuring the performance of the electrical function. The form of the wearable receives limited attention and is often addressed after the development of electronic components.
This research highlights a broader perspective of wearability, extending on the above to encompass interactions between textile and the body in motion, and market expectations around aspects such as durability and access. To better address wearability challenges in e-textiles, this research was conducted through an interdisciplinary collaboration.

Bringing together a team of designers (textiles and fashion) and engineers (mechanical and electrical) highlighted the need for strategies to navigate e-textile research. This paper presents methods utilised to establish shared understanding across the team. It also responds to the predominant positioning of e-textiles to consider existing fields of knowledge within design disciplines and established garment manufacturing systems that could be utilised to enhance e-textile wearability and end-user uptake.

Keywords: E-Textile, Interdisciplinary, Wearability, Textile Design, Communication

INTRODUCTION

Electronic textiles (e-textiles) are textiles "…where electronically conductive fibers or components are incorporated into a textile." (Cork, Dias & Hughes-Riley 2018, p.3). As technical textiles, e-textiles are utilized in consumer and industrial applications, on the body, and in interior and exterior applications of the built environment. The significant potential of e-textiles across a breadth of applications attracts the interest of academics, industry, government agencies and consumers. This paper is specifically focused on wearable e-textiles, referred to as 'e-textiles' for the remainder of this paper. In this form, e-textiles are generally used to sense, and/or respond to, signals from the body through interaction with an electrical device or interface. Further, they are commonly developed as next-to-skin products for use in health, sports, medical and defence sectors (Meena et al., 2023).

Currently, advances in functionality and form of e-textiles commonly result from development of advanced sensors and textile fibres to improve accuracy of measured variables, and improved wearability due to a lower profile of electronic parts or development of novel flexible and conductive materials. Despite these advances, and a growing interest and reliance on e-textiles, there remain challenges with wearability, commercialisation and uptake.

As outlined by Meena et al (2023) constraints impacting the commercialisation and accessibility of e-textiles include needs that are similar to that of developing any mainstream clothing. For example, solutions are needed for scalable, low-cost manufacturing, improved washability and durability, green development and biodegradability of materials. Challenges specifically relating to electrical function in e-textiles include lack of a stable power supply, the seamless and reliable integration of electrical components into textile forms, accuracy of data, and a general lack of standardization to meet market expectations for everyday use (Ruckdashel, Khadse & Park, 2022). As a result of these challenges, costs are high, wearability is inadequate, and uptake and user confidence in e-textiles is limited.

Meena et al (2023) report immense interest in the e-textiles market in the last 10 years. For example, in the health and medical sectors, there is a growing interest in e-textiles because of the consumerisation of healthcare. Enabling individuals to independently measure and track physical health markers such as blood pressure and heart health through digital devices (Cobb, 2019; Huygens et al., 2017) is reliant on wearable technologies (both non-textile such as smart watches as well e-textile forms) to capture relevant data. Meena et al (2023) references an IDTechEx report from 2021 in which the market for wearable e-textiles is forecast to be growing at a rate of more than $1.3 billion per year by 2031. However, the authors also highlight that at the time of reporting, approximately US$0.5 billion of the US$70 billion wearable electronics market is from fabric-based products, indicating significant room for growth if e-textile challenges can be addressed.

As a research area, e-textiles is inherently interdisciplinary requiring expertise across a range of disciplines such as electrical engineering, materials science, textile design, as well as end-use application specific knowledge. Addressing current challenges of e-textiles requires expertise from all disciplines, though with the varied nature of these disciplines, this introduces its own set of challenges.

LITERATURE REVIEW

In the following sections two key contexts are outlined; the wearability of e-textiles with consideration for a broader perspective that could support enhanced wearability, and the challenges associated with the interdisciplinarity of e-textiles.

E-textiles and Wearability

The development of e-textiles has progressed through three product generations. The first, dating from the early 20th century, saw electronic components being attached to the surface of a textile. Still commonly used, this generally results in bulkier wearables, though wearability improves alongside the miniaturisation of electronic components. Prompted by the discovery of conductive polymers in 1977, a second generation resulted in textiles that were generally lighter and more flexible with functions such as sensors and switches, integrated into the textile through elements such as conductive threads and textile coatings. In this 2nd generation, bulkier electronic components still need attachment. Though not common, the integration of electronic function into yarn approximately 20 years ago has allowed for garments themselves to sense and respond in a 3rd generation (Cork, Dias & Hughes-Riley, 2018).

Of note, the three generations of e-textiles are defined through advancing integrations of electrical function within the textile. Alongside this integration, advances in material properties and the size and flexibility of electronic components have all contributed to improved wearability of e-textiles. While this contribution to wearability is commonly understood, this paper explores a broader view of wearability, to emphasise other aspects in the design of e-textiles that could enhance end user experience.

In a garment context, wearability is commonly understood to encompass comfort, practicality, and aesthetic or emotional appeal. It is also influenced by social, cultural or application specific considerations. The inclusion of electrical function results in specific aspects of wearability being given more emphasis, such as safety and thermal comfort. Additionally, the integration of hardware, or components which are generally less flexible than the textile, introduces a wearability consideration related to hardware profile (size, weight and aesthetic). Also impacting wearability is the need for direct and stable contact on the body to ensure reliable and accurate signals are captured such as for EMG monitoring to assess health of muscles and nerves. This needs to be balanced with the need for flexibility and stretch to accommodate body movement and fluctuations in body shape while it is being worn (Ruckdashel, Khadse & Park, 2022).

In their paper on designing wearable computing systems, Gemperle et al (1998, p.1) define wearability as "...the interaction between the human body and the wearable object," further explaining that this encompasses "…the physical shape of wearables and their active relationship with the human form." This interaction or relationship with human form provides a useful way to incorporate a broader set of wearability variables. The relationship of wearability with human form is also referenced by Elmogahzy (2020) who defines three interactive modes in the design of e-textiles; interaction between e-textiles and the wearer, interaction between e-textiles and the external environment / electronic systems, and interactions that meet the specific needs of a product.

The first interactive mode, between e-textiles and the wearer, is of most interest in addressing wearability. Elmogahzy (2020, p.350) notes that this mode should accommodate "...all human-related performance characteristics that have been considered in the design of traditional textiles (e.g., aesthetic, durability, comfort, aesthetic and fashion trends)," while additionally integrating the hard materials of electronic components.

These discussions highlight that wearability encompasses both the measurable aspects of technical performance and functionality, more naturally aligned with standardised and formalised objectives of engineering disciplines, as well as the more subjective considerations of visual aesthetics, tactility, and emotional appeal, which are often rooted in textile-focused perspectives.

Returning to Elmogahzy's (2019) three interactive modes – these modes can also be seen to represent differing discipline-specific focuses. The first mode between e-textile and wearer is positioned largely within textiles, fashion and materials science; the second mode between e-textile and electronic system is located in engineering; and the third mode relating to specific product needs aligns with the discipline of the end-user application area. Of note, the author explains that the design of e-textiles should provide optimum performance across all three interactive modes, requiring contributions across all relevant disciplines.

Developing innovative solutions for garments that include integrated wearable electronics requires a combination of skillsets engaging with interdisciplinary design processes, blending creative design practices with technical expertise. As discussed by van Schaik et al. (2023) "The multidisciplinary aspect of e-textile design necessitates collaboration across diverse fields... designers often struggle to balance aesthetics and functionality while manufacturers face gaps between textile and hardware processes." (van Shaik et al., 2023, p.1).

Interdisciplinary Collaboration

As outlined in the introduction and the section above, e-textiles is inherently interdisciplinary. yet, as Ruckdashel, Khadse & Park (2022) note in their outlook of e-textiles, fostering collaborations in e-textiles is a challenge. While there is substantial literature addressing the interdisciplinary challenges of integrating design and science, the authors (2022, 3.2) report that, "…collaborations for smart textiles span a much wider range of disciplines, sectors, and countries; these include scientists, artists, designers, computer experts, technologists, electrical engineers, manufacturers, and wearers in academia, government, and industry." While these participants may have shared intentions, they can have significantly different understandings and approaches.

There are limited structures, tools or guidelines for collaborative engagement in this area. Described in Coulter's paper on fostering interdisciplinarity between textile design and science, the author notes, "The paths of the textile designer and the engineer seldom cross within the textile industry and although the need for multidisciplinary approaches is clear, there is a lack of literature around the field of textiles to demonstrate how disciplines might work together." (Coulter, 2018, p. 138).

Ruckdashel, Khadse & Park (2022) also highlight the lack of an "e-Textile" journal, with researchers instead publishing in discipline specific journals. They further note that 88% of publications are outside of textile journals, even though almost a third of the researchers have a textiles affiliation. As a result, knowledge tends to remain with individuals or, if developed collaboratively, is likely to be separated again to be disseminated in discipline specific knowledge bases.

Exploring strategies to navigate e-textile research between textile design and engineering practices is a key outcome of this research project and is intended to inform and advance future e-textiles collaborations.

METHODOLOGY

This research results from an interdisciplinary research collaboration between design researchers with expertise in textiles and fashion, and engineers with expertise in biomechanics and electronics. All participants have varying levels of experience in working with e-textiles. However, the group had not worked together previously. A collaborative working format was established with weekly meetings and agendas that allowed for all team members to contribute to open discussions.

Though e-textiles as a research area is inherently interdisciplinary, it does not dictate or necessarily operate within collaborative models. In our experience, electrical function and textile form are often developed independently and consecutively – that is, electronic systems are integrated into textile forms once nearing resolution. Key to the approach of this research was addressing design and engineering criteria simultaneously.

For the textile designers in the team who have expertise in digital knitting, this more holistic approach to product design was a familiar experience. As a constructed textile, mechanical and aesthetic properties of knitted cloth, including the garment form, emerge stitch by stitch as the textile is constructed. This interconnectedness of form and function in the design and production of knitted garments offers a model whereby technical and functional qualities are managed simultaneously alongside aesthetic and form.

Of note, the textiles and fashion researchers are part of an emerging textiles research group. As such, the project was approached with the intention to gain experience and understanding of how best their areas of expertise could be utilised, and, to establish a foundation for ongoing research collaborations.

RESULTS AND DISCUSSIONS

While this project team was established to develop low-cost, aesthetically considered e-textile connectors, the team quickly realized the importance of establishing shared understandings of language, design criteria and processes. Methods adopted to develop shared understanding are discussed below. Further, the discussion considers whether existing fields of textile and fashion knowledge could be better utilised to address e-textiles challenges with wearability and commercialisation.

Shared understanding

Engineers and textile designers use discipline-specific terminologies and processes that may lack direct equivalents, or represent alternative meanings, in each other's fields. Developing a shared understanding of verbal and written language, and of visual representations can assist in unifying vocabularies between the two disciplines and thus limit misunderstandings.

In this project, an accessible format for aligning both text-based and visual communication of concepts was identified as an early requirement towards achieving innovative and cohesive design outcomes. In part, this is recognizing the tacit understandings and implicit knowledge biases that each researcher brings to the collaboration. Developing strategies to articulate such understanding and being open to alternative perspectives was key to facilitating clear and effective collaboration.

Terminology

One such strategy was a terminology review, consolidating varied meanings towards singular definitions, agreed and understood across the research group or, substituting words with analogous terms where the implied meanings of substituted words were more easily differentiated across disciplines. For example, in Figure 1, 'conductive fibre', though naturally envisioned in differing materials by textile designers and engineers, still hold a shared meaning of a material fibre able to conduct electricity. Terms such as conductive yarn and conductive wire can be adopted to differentiate between materials when needed.

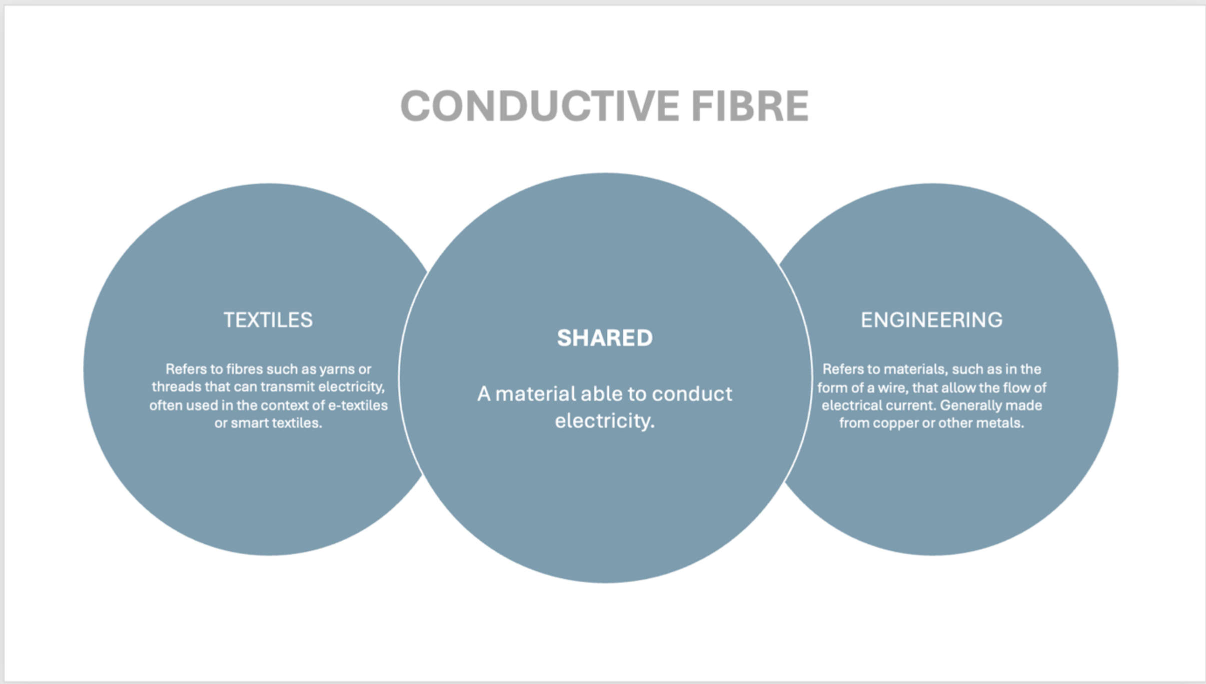

Fig. 1: E-Textiles Terminology Review: Conductive Fibre, 2024.

In contrast 'form', shown in Figure 2, has different implied meanings in each discipline. In the context of designing textiles and garments, form may refer to shape, structure, or silhouette. In the context of designing products or components in engineering, form might reference the physical characteristics of a part such as its shape, size, weight and mass. Or, the form of an electrical circuit may be viewed as the physical configuration or arrangement of electrical components, such as circuit forms or the shape of an electrical signal. Combined, form is then seen to encompass aesthetic and functional dimensions, factual and subjective characteristics, and both 2-dimensional and 3-dimensional formats. In this case, it was useful to clarify the terms used across disciplines to develop shared understanding. For example, in the e-textiles context, an engineer's use of the word 'form' could be substituted with the term 'configuration.'

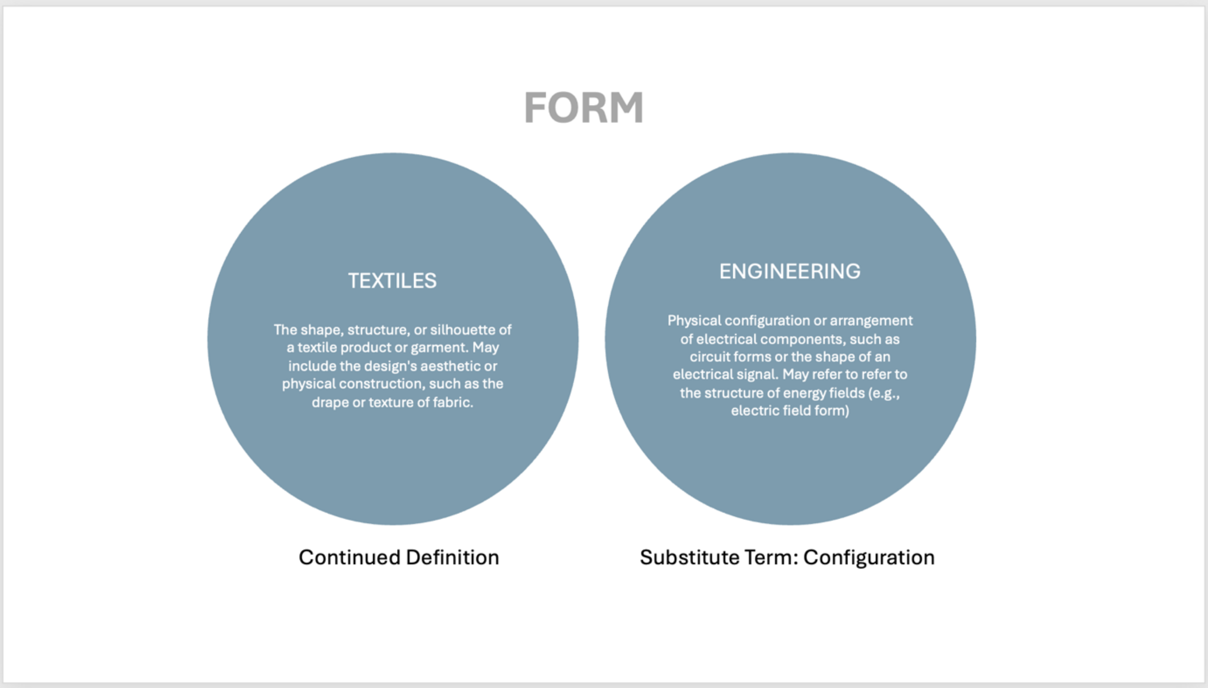

Fig 2. E-Textiles Terminology Review: Form, 2024.

The terminology review was treated as an ongoing process, revisited as needed when it was clear that different interpretations were being adopted in discussions, or to include new words. By acknowledging multiple definitions of a term, agreeing on a singular definition, and/or providing alternative terminology, the documentation ensures consistent communication between all team members. Further, this collaborative approach provides insight into language and processes of collaborator's disciplines, enhancing interdisciplinary understandings.

Visual Language

This project also highlighted the need for shared understanding through visual language. Diagrams or other visual images are essential to efficiently articulating design and functional intentions in the early phases of concept development and exploratory prototyping (McCann, 2009, pp. 87-88). As the purpose and approach of concept ideation and prototyping varies for each discipline, the information captured in the visuals will also differ. When designing e-textile garments, designers should combine design-centered conceptualisation and technical considerations (Zhang, Jenkinson, 2024, p. 590). These may include iterative sampling phases, sketching, mood boards and technical drawings. A focus on aesthetic and experiential qualities emphasises a concept's visual, tactile, and form-based aspects.

Electrical engineering practices may use similarly iterative processes communicated through technical diagrams, physical and digital models, and digital drawings. Schematics for communicating concepts are often characterised by detailed models capturing technical and functional information (Eder, 2013, p. 259). The use of standardised symbols and conventions allows for technical information to be conveyed clearly and unambiguously, with an emphasis on the functional relationships of components. However, accurate interpretation depends on a reader's fluency in the symbols and annotations.

An integrated drawing format was developed to acknowledge and capture each discipline's differing needs and priorities while seeking to quickly consolidate these diverse approaches to communicate concepts across the team. Figure 4 combines 2D and 3D diagrammatic viewpoints, displaying an overview of functional design considerations described on the left and technical unit details on the right. A colour-based key was used to identify the different functional roles of the various components. Combining visual data from textiles and engineering perspectives into one image allows for a single concept drawing to be shared and understood across the team, effectively consolidating a broad range of information into manageable and coherent design drawings.

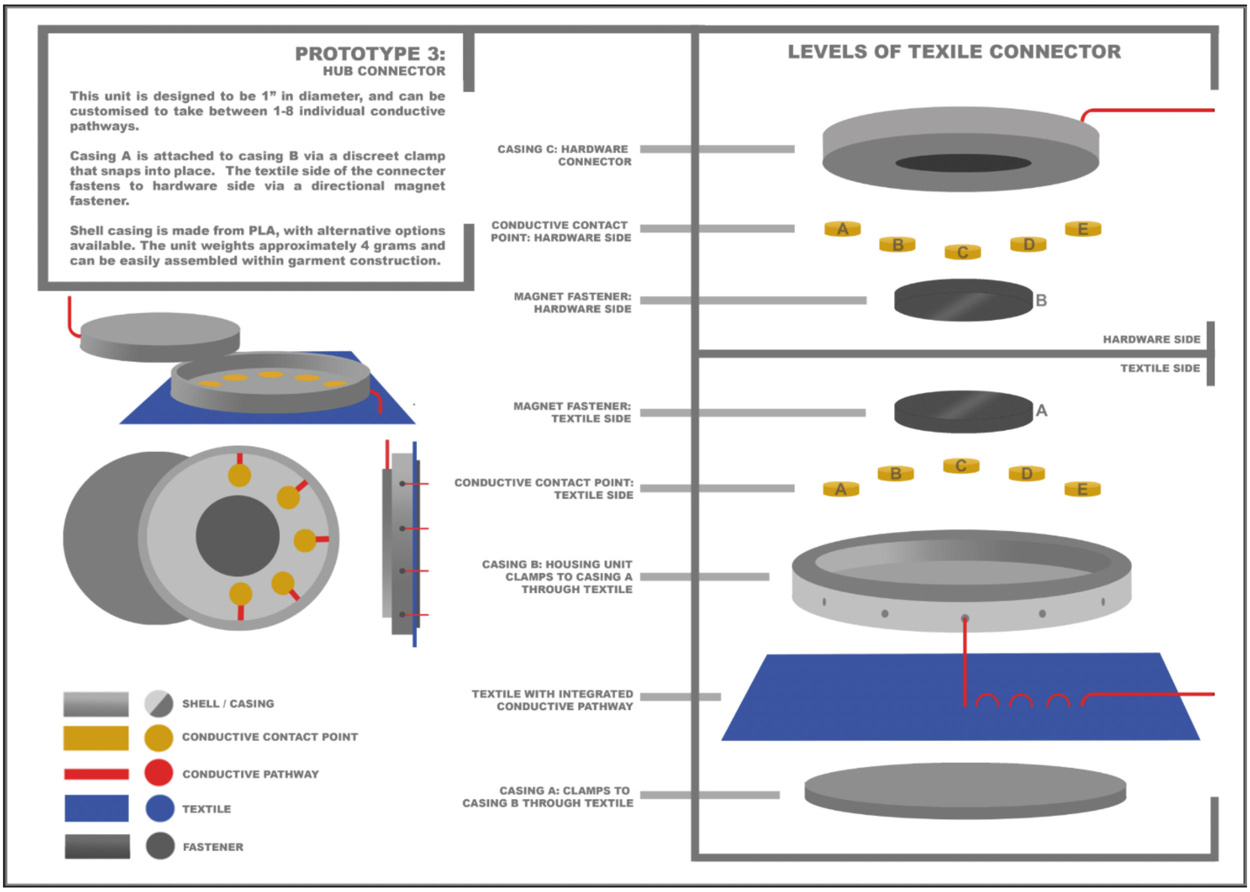

Fig 3. Concept Drawing. Prototype 3: Hub Connector, 2024.

In summary, the challenges of working in interdisciplinary teams across discipline specific knowledge bases with varied terminology and processes are widely referenced. The methods discussed above were found to be effective in supporting a shared understanding across the collaborators. Of note, these methods rely on open discussion and engagement with all participants.

Accessing existing fields of knowledge

The predominant positioning of e-textiles in engineering and materials science disciplines has been discussed previously. In this section, four existing fields of knowledge in textiles and fashion design were identified as having potential to address challenges with wearability, commercialisation and the uptake of e-textiles.

Lines of Non-Extension

Lines of non-extension (LoNEs) are biomechanical notional lines that cross the human body, highlighting where there is minimal strain during motion. That is, areas where neither stretching or contraction occur when the body moves. These lines are identified through mapping “borders or creases in the skin that do not stretch when a joint is moved or when skin is pulled” (Binedell et al., 2020, para. 3). LoNE’s were first observed by physicist and engineer Arthur Iberall when designing a spacesuit in the 1940’s. To function effectively, high internal pressure needed to be maintained in the suit, achieved through non-stretch rigid elements in its construction. To allow for mobility when worn, Iberall analysed parts of the body that did not move as much, and thus could be treated differently, resulting in suits that had “natural mobility and minimal ballooning” (Iberall, 1970, p. 251).

JinYun (2013, p. 12) references LoNEs, or skin deformation as cited in design-based studies, to achieve “functional power with aesthetic appeal” in high tech sportswear. Compression garments, which act as a second skin to improve performance, are provided as an example highlighting that considerations need to be made for mechanical sensations, resulting from textiles being in direct contact with the skin (JinYun, 2013). Placing seams over parts of the body where there is the least stretch and elongation during physical activity improves the comfort of the wearer. Bragança et al. (2017) further report that sportswear must accommodate variations over a bending joint to avoid hindering movement and or creating discomfort.

Achieving comfort and mobility are ongoing challenges in e-textiles due to hard, non-fibrous and non-stretch electronic components. Principles of LoNEs and high-performance sportswear design could be utilised to inform placement of these components in areas of reduced stretch and movement, as well as informing general design and comfort of fitted garment forms, all contribute to enhancing wearability of e-textiles.

Cultural, Historical and Fictional References

Design processes vary across engineering and textile design, reflecting each discipline's goals and methodologies. Engineers may use structured frameworks and scientific principles to inform concepts; adapting or innovating with technologies, materials and systems and prioritising functionality and problem-solving. Textile designers, particularly those with a creative leaning, draw heavily on cultural, historical, and fictional sources to explore aesthetics and innovation (Smith, 2016, p.11). Examples of projects that have referenced historical or fictional contexts to generate innovative design outcomes are discussed below, focusing on the potential these offer in the design of e-textiles.

The merging of hard and soft components in historical dress reflects complex craftsmanship. This blending of materials into a wide range of silhouettes and garment mirrors textile-centered challenges in e-textiles, where hardware and circuitry are integrated into soft and, in some cases, delicate textiles in varying forms. The potential for costume, fashion and textile references to inspire the conceptualisation of wearable technology is demonstrated in the 'Electric Corset' project, a collaboration between researchers at Nottingham Trent University and Nottingham City Museums and Galleries Costume and Textiles Collection. Kettley et al. (2017) note that the modularity and lack of constructed details in contemporary fashion limits the opportunity to ponder technical enhancements and placement of structured components, as are needed in e-textiles. Through surveys of historical dress, the authors aim to "…identify potential spaces between the body and clothing, where actions, objects and technology can co-exist." (Kettley et al., 2017, p. 489)

During this project, articulated elements of historical armour were reviewed, considering how this construction might enable flexible yet strong components. For example, armour's layered construction may support the integration of sensors, LEDs, or flexible circuits into textiles. Additionally, the segmentation of plate armour suggests modular wearable designs, while chainmail's interlinked patterns offer pathways for developing flexible electronic fabrics.

Fictional sources also offer design inspiration by imagining unrealised e-textile forms. For example, SixthSense, a wearable gestural interface released in 2009, references gestural control performances seen in 2002's Sci-Fi Action film Minority Report (Mistry & Maes, 2010, pp.33-35). Developed at MIT Media Lab, this device combines a projector, camera, and mirror in a wearable device to augment the physical world with digital information. Similarly, Nike's self-lacing shoes, first released in 2016, directly imitate the iconic scene in Back to the Future II where Marty McFly's "Nike Mags" laces tie automatically. Nike's development of these self-adjusting laces reflects a blend of technological imagination and practical application, showing how a fictional concept can fuel real-world technological advances (Hansen, 2010).

The examples above demonstrate how historical and fictional sources offer novel perspectives on design, functionality, and user interaction. While these unconventional references may not be immediately practical from a prototyping and manufacturing perspective, they highlight alternative approaches to envision new possibilities. These sources of inspiration can also be used to communicate innovative concepts that might otherwise be difficult to convey.

Manufacturing

Commercialisation and user accessibility of e-textiles is currently limited by uncertain or non-existent pathways to scalable production in addition to high costs for specialist materials and/or manufacturing methods. Posch & Fitzpatrick (2021) note that textile and engineering toolboxes differ due to the materials and processes of each discipline. Consequently, e-textiles are primarily developed through a diverse set of tools. The authors further highlight that the tools for integrating electronic components with textiles – that is, "...the productive means that bring eTextile artefacts into being (2021, p.4:2)," remain unexplored. The development of new tools, and specialist making systems for e-textiles, are presented as opportunities to improve commercialisation.

In this project, an alternative approach was considered that focused on reducing the need for hand construction or specialist equipment, and instead, utilising existing manufacturing systems. As such, the team established a criterion around prioritizing existing tools and fabrication in the development process. Established manufacturing systems that could support wearables production and scalability were reviewed. Figures 4 - 6 below present a summary of findings for three systems, covering an overview of the construction technique, cost and accessibility, and other considerations towards answering e-textile challenges.

MANUFACTURING SYSTEM: DIGITAL EMBROIDERY

Overview	Embroidery is "decoration worked on the surface of the fabric using thread." (Devi et al. 2019, p. 127). Traditionally used to add or create patterns on a textile for embellishment, in a manufacturing context "embroidery is largely produced on computer controlled embroidery machines" (Devi et al. 201, p. 127). The design is physically attached through a series of loops which enclose the textile both on the front and the back of the fabric. The availability of conductive embroidery thread allows for conductive pathways to be embroidered directly onto an already constructed textile.
Cost and Access	- Industrial embroidery can be accessed at lower cost than digital knitting. - Ease of access to domestic embroidery machines supports low-cost prototyping. - Conductive thread supply is limited and moderate cost.
Other	Produces a second-generation e-textile. Although a strong connection is established between textile and electronics it does not produce a fully integrated system as for digital knit. The addition of stitches to an already constructed fabric can affect the material properties of the textile, e.g. reduction of stretch capabilities. A minimal waste fabrication process, only using the thread required to create a trace or circuit, hence contributing to sustainable production.

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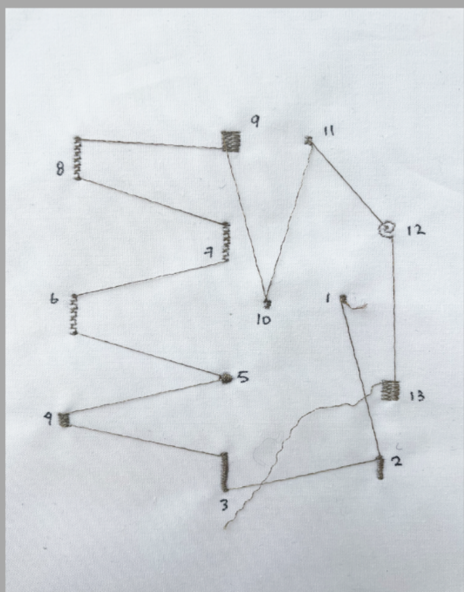

Embroidered Conductive Pathway.

Fig 4. Digital Embroidery, 2024

MANUFACTURING SYSTEM: DIGITAL KNITTING

Overview	Embroidery is "decoration worked on the surface of the fabric using thread." (Devi et al. 2019, p. 127). Traditionally used to add or create patterns on a textile for embellishment, in a manufacturing context "embroidery is largely produced on computer controlled embroidery machines" (Devi et al. 201, p. 127). The design is physically attached through a series of loops which enclose the textile both on the front and the back of the fabric. The availability of conductive embroidery thread allows for conductive pathways to be embroidered directly onto an already constructed textile.
Cost and Access	- Industrial embroidery can be accessed at lower cost than digital knitting. - Ease of access to domestic embroidery machines supports low-cost prototyping. - Conductive thread supply is limited and moderate cost.
Other	Produces a second-generation e-textile. Although a strong connection is established between textile and electronics it does not produce a fully integrated system as for digital knit. The addition of stitches to an already constructed fabric can affect the material properties of the textile, e.g. reduction of stretch capabilities. A minimal waste fabrication process, only using the thread required to create a trace or circuit, hence contributing to sustainable production.

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Knitted Conductive Pathway.

Fig 5. Digital Knitting, 2024

MANUFACTURING SYSTEM: INDUSTRIAL SCREEN PRINTING

Overview	An industrial mass production replication technology, whereby conductive inks are pushed through a mesh onto a textile. Ink sits on the cloth, rather than being fully integrated. Each ink layer, or colour, is printed separately, allowing for specific placement of traces (Board 2003)
Cost and Access	- Lower-cost conductive textile production technique (Tian 2023) - Reasonably efficient with ink applied in areas of traces. - Ease of access to manual screen printing supports low-cost prototyping. - Accessibility would likely increase with demand
Other	Produces a second-generation e-textile. Longevity of the electronic traces can be limited due to bonding of ink and textile. Through wash and wear, as well as the movement of the fabric underneath the print there is a higher deterioration rate of the traces. "Durability is currently a barrier to use screen-printed textile electronics" (Paul et al. 2014, p. 1).

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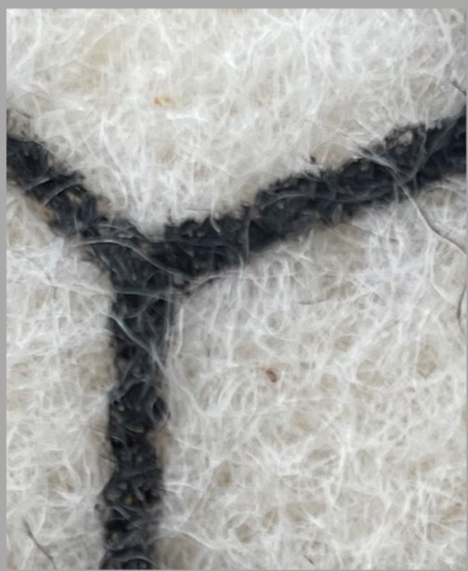

Screen Printed Conductive Pathway.

Fig 6. Industrial Screen Printing, 2024

Designing wearables with clear pathways to established, low-cost manufacturing systems would support commercialisation and end user accessibility of e-textiles. Establishing these considerations as project parameters or design criteria ensures they are present in design decisions throughout the project.

Connectors

Connectors are commonly used in both textile and engineering disciplines. However, the detail and meaning of the term differs for each. Establishing a shared understanding of 'connector' is another example of a term that needed review, acknowledging perspectives from both disciplines to inform a shared understanding towards the projects aim of designing wearable e-textiles connectors.

In textile design, a connector is understood as a fastener. That is, "as a piece of hardware that connects two items; is relatively easy to connect and disconnect; and, when connected, tends to stay connected" (Everett & Moyer, 2015, p.12). Everett and Moyer further clarify that fasteners are intended for repeat use unlike adhesives or tapes (2015). A fastener is evaluated on usability, strength and aesthetic with its primary function being to fasten or close a garment on the body, or parts of a garment such as a pocket.

In electrical engineering a connector is understood as "an electromechanical component that provides a separable interface between two parts of an electronic system without compromising the performance of the system" (Kyeong & Pecht, 2020, p.1). The function of a connector in this discipline is to complete an electronic circuit, with function often prioritised over form.

Hunt et al. (2021) discuss e-textiles connectors using terms such as *detachable joining technologies*. When reviewing each discipline's understanding of connectors, it became clear that fasteners act as connectors but are not necessarily a component of an electrical circuit. In contrast, electrical engineering connectors take the form of an electronic component but are not necessarily used as fasteners. Also emerging from the review was the need to identify the different types of connectors that are needed in a wearables design. For example, connections may need to be permanent, detachable, flexible, washable etc. Different connector definitions were established recognising that connectors on different points of a garment or circuit need to be designed to meet differing criteria. This allowed for clothing and textile fasteners, which are generally highly wearable, to be evaluated against the needs of the varying connector profiles. The immense range of fasteners in clothing and textiles provided numerous sources of inspiration for this project.

CONCLUSION

This paper presents key findings from the initial phases of interdisciplinary research project aimed at developing connectors that enhance the wearability of e-textiles. These include the need for a broader criterion of wearability and for strategies to support shared understanding between designers and engineers.

An extended understanding of wearability was developed encompassing a breadth of variables, both technical and subjective, that contribute to user satisfaction and uptake. A framing of wearability, as an interaction or relationship with the body in motion, proved useful to encompass this breadth of variables and has been adopted by the team.

Existing fields of knowledge in textiles and fashion that could enhance e-textiles wearability were considered resulting in three key contexts informing this research. LoNEs have the potential to improve wearability through analyzing placement of inflexible components on the body. Cultural references such as armour and historical dress provide insight into the integration of hard componentry into textiles, and film references inspire novel wearable forms. Garment fasteners are highlighted as existing and familiar 'connectors' that could be adapted to develop wearable e-textile joining technologies. As this interdisciplinary project moves from a discovery and conceptualisation phase into the prototyping of novel connectors some of these findings will be further investigated through practice.

To address challenges in the commercialisation of e-textiles, affordability and accessibility were adopted as design criteria from the start of this project. Three industrial manufacturing methods are reviewed. The team have access to these technologies for prototyping, allowing for production ready developments.

Key challenges of interdisciplinary collaboration between textile and engineering practices are outlined, recognizing the distinct knowledge and processes of each discipline. The importance of developing shared understanding to inform a collaborative approach is highlighted through strategies that consolidate text-based terminologies and visual representations. While these methods will be used in future projects, it is important to recognize the time allowance needed to engage with them. In industry collaborations, this time allowance may be prohibitive. The team intends to develop templates for terminology reviews and visual communications in accessible formats to support future use.

Of note, Elmogahzy's (2019) 3rd interactive mode of wearability - interaction that meets the specific needs of a product – is still to be addressed. The function of being wearable should include an understanding of user needs with considerations for varying demographics and contexts of use. This will also inform the use of connectors, especially for demographics where dexterity may be limited.

This research is ongoing, and as such, is not conclusive in its findings. Developing innovative solutions for e-textiles, with a focus on wearability and commercialization are not new challenges, being addressed by researchers and industry for some decades. This paper highlights a few areas where discipline specific knowledge bases could be accessed through collaborative and synchronous design approaches to enhance wearability and user uptake.

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