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Design considerations for the creation of electronic yarns for wearable health monitoring devices

Arash M. Shahidi, Kalana Marasinghe, Parvin Ebrahimi, Carlos Oliveira, Nishadi Perera, Amanda Briggs-Goode, Tilak Dias and Theo Hughes-Riley

Nottingham Trent University, Nottingham, UK

ABSTRACT
Textiles with embedded sensing capabilities can be an ideal solution for many health monitoring applications as textiles are comfortable to wear close to the skin. Various integration techniques have been explored over the years to create textiles and garments with electronic functionality. One method is to embed electronics within the core of a yarn that is then used to produce textiles. The method discussed in this work accomplishes this by soldering a component onto conductive wires, encapsulating them within a discrete resin pod, and then covering the wires and component in a fibre sheath. This electronic yarn can be incorporated into textiles to produce wearable garments. This technology has already been used to create a variety of textiles with different functions. The literature has shown limitations with the existing electronic yarn design, and this work discusses how these limitations can be overcome.

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Electronic textile, e-textile, wearables, smart textiles, electronic yarns

Introduction

Electronic yarns (E-yarns) can be used as a means to incorporate electronics into the core of textile yarns that can then be used to create textile garments. This electronics integration technique can result in textiles with normal properties, such as heat and moisture transfer characteristics and breathability (Shahidi et al. 2024), so they will be comfortable to wear against the skin, which is important for end user acceptance. This is desirable for many wearable sensing applications, including those for health monitoring, where wearing the sensing element close to the body is important for accurate readings and comfort is critical to ensure user compliance.

CONTACT Theo Hughes-Riley theo.hughes-riley@ntu.ac.uk Nottingham School of Art and Design, Nottingham Trent University, Nottingham, UK

While a wealth of fibre- and yarn- type electronics exist (Dang et al. 2024), this work specifically focusses on a type of electronic textile which is created through the soldering of small-scale electronic chips onto conductive wires, the encasing of these components within a resin micro-pod, and the covering of the ensemble within a fibrous sheath. This is referred to as electronic yarn, or E-yarn, technology, and this has been employed to create a variety of health monitoring devices including temperature sensing socks (Hughes-Riley et al. 2017) and near-fall detecting socks (Rahemtulla et al. 2023). Work with this technology has been largely restricted to a handful of researchers, and this is reflected in the cited works in this article. This work details the limitations of early electronic yarn (E-yarns) designs, means of improving the design, and presents a study on how different braiding parameters can affect the final covering of the E-yarn.

Background to electronic textiles

There have broadly been three techniques for incorporating electronics with textiles (Hughes-Riley, Dias, and Cork 2018), and each method may result in different end properties. The most common method is the surface integration of electronics, where the textile is made and the electronics are added afterwards. This can be accomplished using various methods, including inserting the electronics within a pocket in the textile or attaching the electronics to the surface of the textile (for example using bonding or embroidery). In these cases, the electronics can generally be felt, and their incorporation will affect some of the fabric properties, such as the drape characteristics (this describes how a textile hangs under gravity) or air permeability (describing the ability for air to pass through a material). If, for example, a flexible electronic panel is bonded to a textile it will obstruct the porous textile structure preventing moisture and air transfer. Flexible electronics are incapable of shear so by combining it with a textile it will no longer be able to drape. While this is intuitive, quantified evidence of this is mostly lacking in the literature. These integration techniques can be appropriate for some applications (such as tents or outerwear) but can affect user comfort if worn close to the skin. Methods of integration that see electronics attached to the textile can also significantly affect the appearance of the textile, limiting design choices. Printing electronics directly onto textiles is also a type of surface attachment, and significant research has been conducted exploring screen-printing (Janczak et al. 2019) and ink-jet printing of electronics onto textiles (Carey et al. 2017). This can lead to textiles with more normal properties.

An alternative integration method is to knit or weave conductive elements: either metal or metal-coated yarns, conductive polymers or polymer-coated yarns, or carbon nanotube fibres. This integration technique became prominent following work by the Georgia Institute of Technology (Gopalsamy et al. 1999), who developed the 'Wearable Motherboard™', and the Massachusetts

Institute of Technology (Post et al. 2000) who demonstrated devices created through the weaving of conductive materials in the late 1990s. This method of integration is excellent for creating electrical connections between electronic devices and for devices that only require a conductive area, or areas, to function, such as electrocardiogram electrodes for measuring heart rate (Hughes-Riley et al. 2019), temperature sensors (Husain, Kennon, and Dias 2014), and heating elements (Zhang et al. 2017). This integration technique is known to have some limitations: it will affect the surface appearance of the fabric, the electronic functionality can be influenced by external factors including temperature (which is why they can act as temperature sensors) or sweat (as this will affect the conductivity). Sensors are also known to be influenced by hysteresis, a lag in the sensor response if deformed. For example, this has been shown for a pressure sensor developed by Meyer et al. (Meyer et al. 2010). There are also some durability issues, such as to mechanical abrasion as shown by Shahidi et al. when studying the durability of electrodes designed for heart rate monitoring (Shahidi et al. 2021).

An emerging method for integrating electronics is to incorporate the complete electronic functionality within a fibre or yarn and then incorporate this during the textile manufacturing process or as a post-process. These techniques are currently largely constrained to academia, and the range of devices of this type are diverse (as shown by a recent review (Dang et al. 2024)). Many yarn or fibre-based electronics are created by combining materials in a yarn or fibre shape. An example is an electroluminescent fibre made by Bellingham, Bromhead, and Fontecchio (2017) where different materials were layered over a conductive core material. An excellent review by Loke et al. (2020) provides an overview of functional fibres developed by thermally drawing materials. An alternative methodology is to integrate electronic chips or bare dies into the fibre or yarns, for example, the electronic fibres developed by MIT (Loke et al. 2021). Flexible printed circuit boards populated with components have also been incorporated into yarns, allowing for the incorporation of complex functionality; for example, this technology has been used to embed accelerometers into textiles (Li et al. 2020). Yarn and fibre-based technologies can also be used to create a partial device, which can be combined with other functional fibres during knitting or weaving. For example, a textile solar panel where a mostly complete solar cell and the counter-electrode were brought together during the weaving process (Liu et al. 2018).

A summary of the key different electronics integration techniques for creating E-textiles is presented below (Table 1).

Electronic yarns

E-yarns are ideal for creating sensing devices for healthcare applications as in principal any commercially available sensor can be incorporated into the yarn (allowing for a wide array of potential functionality): The limitation being that

Table 1. An overview of key differences in electronics integration techniques for the creation of electronic textiles.

Consideration	Technique: Surface integration of electronics	Structural integration of electronics	Yarn or fibre integration of electronics
Concept	Adds electronic after the production of the textile.	Adds electronics during the production of the textile.	Adds complex electronics at the yarn or fibre level.
Device types	Not restricted by the technology.	Limited to creating interconnections and devices that use large conductive areas to operate such as heaters and electrodes.	Not restricted by the technology.
Textile properties	Can affect key properties including air and moisture permeability, and drape.	Generally have normal textile properties.	Generally normal textile properties, however this is likely dependent on the exact technology used.
Appearance	Can affect appearance, however electronics can be hidden in some cases, for example in pockets.	Electronics will be visible on the surface of the textile.	A normal appearance can be achieved.
State of development	Most electronic textile products are created using this technique.	Some electronic textile products are created using this technique.	Currently restricted to the research setting.

the size of the integrated device will influence the size of the final yarn. The E-yarns can be incorporated into existing types of worn garments with relatively little need to alter the design, and the presence of the E-yarn is unobstructive to the end user. Currently, such devices are at a research stage, with the E-yarns created using this process not being commercially available.

E-yarns have previously been used to develop various sensing devices with a focus on healthcare, wellbeing, and personal protective equipment. Devices have included temperature sensing garments for the prevention of over-exposure to cold and damp conditions (Hughes-Riley et al. 2017), acoustic sensing textiles to monitor noise exposure (Hughes-Riley and Dias 2018), a vibration sensing glove to monitor hand vibration exposure (Rahemtulla, Hughes-Riley, and Dias 2021), an over-sock that can monitor for falls and near-falls (Rahemtulla et al. 2023), and a glove capable of measuring pulse rate (Peiris et al. 2024).

Through a series of studies and trials developing and testing prototypes over the course of many years limitations in the original E-yarn design were identified. These could lead to failures in the device which required rectifying. Addressing these issues would be essential for the eventual commercialisation and adoption of this technology. This paper is an account of the issues identified with the E-yarn design and the steps taken in redesigning the E-yarn to address these challenges.

A wealth of literature has seen multiple different E-yarn types being developed (as discussed above), and key early developments included devices capable of temperature sensing (Hughes-Riley et al. 2017), illumination, and light sensing (Satharasinghe, Hughes-Riley, and Dias 2018). The components used to construct these E-yarns (thermistors, light-emitting diodes, and photodiodes) had two electrical connections that needed to be soldered. The temperature, light sensing, and illuminating E-yarns were constructed using similar processes and materials. Each component was soldered onto a thin, multi-strand copper wire (seven strands, single strand diameter = 50 µm; Knight Wire, UK; Figure 1(a)) using a focussed-beam infra-red reflow soldering technique: a PDR IR-E3 Rework System (Cardiff, UK) and liquid solder paste (SolderPlus S965D500A6, Nordson EFD, Dunstable, UK) were employed. The wire was highly flexible but would hold its shape if bent at a sharp angle (see Figure 1(c)). The soldered component(s) would then be encapsulated within a micro-pod made from a UV curable resin (Dymax, 9001-E-V3.5, Dymax Corporation, Torrington, USA) along with a multi-strand Vectran™ yarn (20 filaments; Vectran, Kuraray America Inc., USA; Figure 1(b)). Vectran is spun from a liquid crystal polymer, producing a final yarn with a very high tensile strength. This was critical to protecting the copper wires and the component from mechanical stress, such as the pulling or twisting experienced throughout the production process or during use, as these wires could be easily broken by hand. The size of the component determined the micro-pod diameter

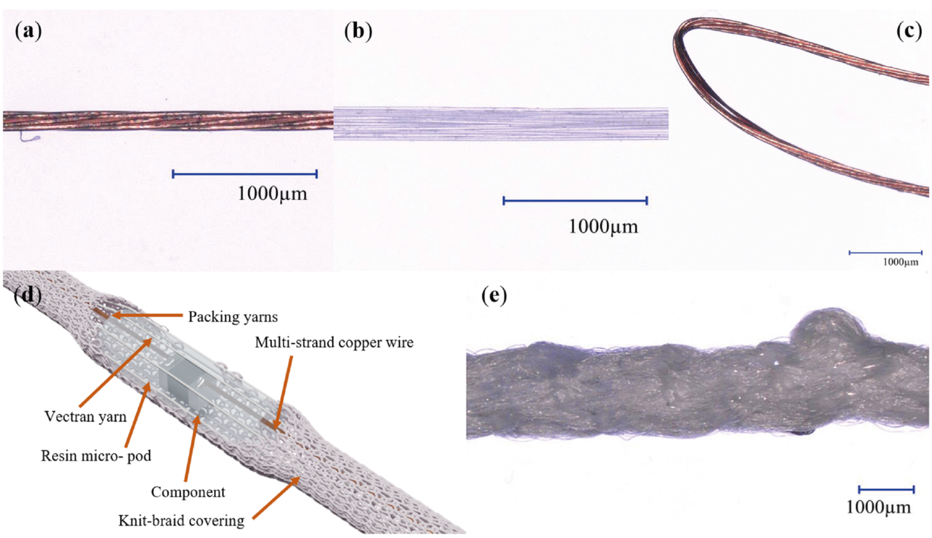

Figure 1. Microscope images showing some key materials used to construct the E-yarn. (a) A microscope images of a seven-strand conductive copper wire. (b) A microscope images of a multi-strand Vectran yarn. (c) A microscope images of a copper wire holding its shape after being bent. (d) A schematic of the interior of an E-yarn. (e) A microscope image of an E-yarn with an embedded thermistor.

and length. It was desirable to minimise the size of the micro-pod, and the micro-pods would typically not be much larger than the component.

Finally, the encapsulated component, copper wires, and Vectran yarn would be fed through a knit-braiding machine (RIUS MC-Knit braiders, RIUS, Barcelona, Spain). To help ensure the uniformity of the E-yarn a set of polyester packing fibres were also fed into the knit-braider surrounding the component-wire ensemble. This would form the final E-yarn. For illuminating E-yarns, or those with an embedded temperature sensor, the final yarns had a diameter of around 1 mm. Figure 1(d) shows a schematic representation of the interior of the E-yarn, while Figure 1(e) shows a photograph of an E-yarn with an embedded thermistor.

Components were electrically connected in series when multiple components were needed within a single E-yarn, such as when creating illuminating garments that required multiple light sources.

Identified challenges with the electronic yarn design

While this E-yarn design could produce robust electronic textiles, the literature has shown that there were limitations. Literature covering the building and testing of prototypes made with E-yarns highlight four key problems with the initial design: issues with the yarn covering and the copper wire protruding through the outside fibre sheath (mentioned in Hardy, Anastasopoulos, et al. 2020; an image illustrating this issue is shown in Figure 2), the influence of sweat on functionality (Hughes-Riley et al. 2021), breakages in the copper interconnections (Hardy, Rahemtulla, et al. 2020), and restrictions when incorporating complex components (for example accelerometers, as mentioned in Rahemtulla, Hughes-Riley, and Dias 2021). These problems ultimately occurred in the E-yarn design due to its unique structure compared to other yarn and fibre-type electronics. These limitations could be addressed by improving two areas of the yarn's design; the covering technique used, and the wire used for the electrical interconnections.

E-yarn covering process

The embedded wire would sometimes migrate through the surface of the knit-braid structure (Figure 2) which raised issues with both the yarn's appearance and durability. With a protruding wire, there was a significantly higher chance of damage occurring to the wire due to abrasion or the wire getting caught on something.

One method employed to mitigate this issue was to first twist the copper wire (including the soldered component) around three cotton yarns using a twisting machine (Hardy, Anastasopoulos, et al. 2020). This consolidated the inner structure and reduced instances of the copper wire protruding through

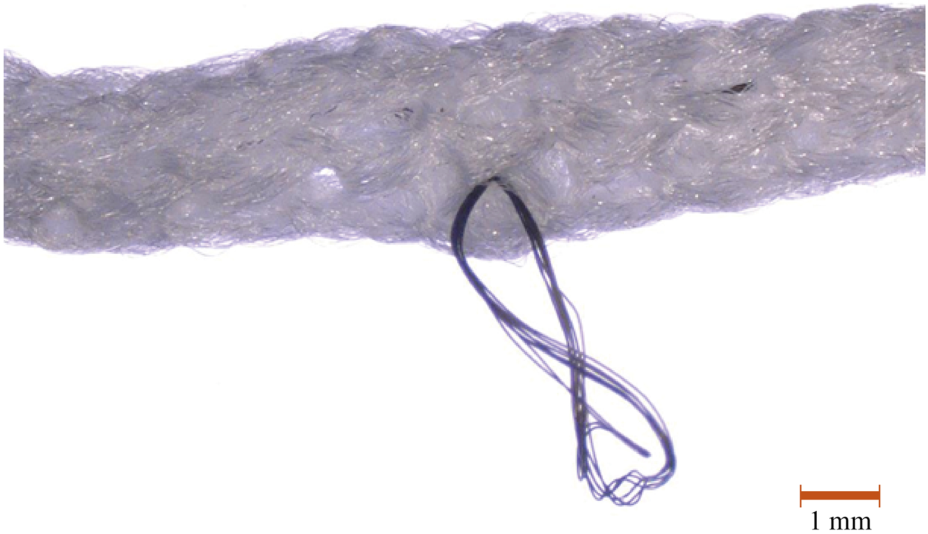

Figure 2. A microscope image of an E-yarn showing a conductive wire migrating through the knit-braid.

the surface. Despite this, the use of this twisting step was not ideal as it introduced an additional production step in the E-yarn's construction. This would add to the time taken to produce E-yarns and ultimately add cost to a final product.

As an alternative to using a knit-braiding, conventional braiding was found to produce a very good covering over the wires and micro-pod. Braiding also more easily facilitated the covering of different sizes of micro-pod, as knit-braiding was restricted to the cylinders available for the knit-braiders: This would result in the final yarns being much larger than the embedded micro-pod if a suitable cylinder was unavailable. Examples in the literature have included using a braiding technique to cover encapsulated solar cells, which have a relatively thin, cylindrical encapsulation (Abeywickrama et al. 2023), and inertial motion units, which have a relatively large, cuboid encapsulation (Rahemtulla et al. 2023). Table 2 summarises the key features of technique.

To ensure that a good coverage and flexible braid was always achieved experimental work was necessary to understand the correct braiding parameters using different materials. Given the importance of the final covering of the encapsulated components on the durability and appearance of the final yarn, in this work different materials and braiding parameters were explored to systematically understand how different parameters would affect the final

Table 2. Summary of the key features of different E-yarn covering techniques.

	Technique	
Consideration	Knit-braid	Conventional braid
Coverage	Creates a relatively porous structure.	Can be used to create a tight structure.
Size	Restricted to available cylinders.	Can produce almost any size of braid and can easily cover different micro-pod geometries. The width of the braid can be varied at different points.
Wire protrusion	In E-yarn production, wires would sometimes protrude through the surface.	Wires do not protrude through the surface of the braid if correct parameters have been selected.

appearance. A Herzog® RU 1/24-80 braiding machine (Oldenburg, Germany) was utilised to produce the braids.

The desired parameters for the final covering would potentially change based on the intended application for the E-yarn, meaning that there would not be one 'correct' set of braiding parameters for each material. For example, while uniform coverage was always desired, the level of fibre coverage for lighting or solar energy harvesting applications might be less than for a physical sensor. The lay length was a key parameter to optimise, which directly corresponded to the tension applied to the yarns during braiding. A short lay length would provide a tighter braid, while a longer lay length would give a loser braid. Another factor affecting the level of coverage was the number of yarn carriers used in the braid: the braiding machine used in this work could use either 12 or 24 carriers. Produced samples were analysed qualitatively based on the appearance of the final yarn, as ultimately appearance was one of the key parameters that was being considered. Four material types were explored: polyester, nylon, monofilament, and cotton (Figure 3). Polyester was chosen as it was the most commonly used covering material for E-yarns in the published literature (for example, Hughes-Riley et al. 2017, Lugoda et al. 2022). Cotton was chosen as it is the most commonly used natural textile fibre. Nylon was chosen as an early synthetic fibre which is in common use. Monofilament was selected as when braided it will give large pours in the structure, which may be useful for optical applications. Ultimately the authors acknowledge that this is not a comprehensive set of textile fibres, and that other materials may be desired depending on the end application.

Figure 3(a) shows covering trials conducted with polyester yarns (1/167/48 from J. H. Ashworth & Son Ltd., Hyde, UK), over a 1.5 mm diameter and 8 mm long cylindrical micro-pod, which represented the type of micro-pod used for many common applications such as for LED embedded E-yarns and temperature sensing E-yarns.

Here it can be clearly observed that the best overall coverage was achieved using 24 yarn carriers with a short lay length (5 mm; Figure 3(aiv)), however a longer lay length with the same parameters (15 mm; Figure 3(avi)) provided a more uniform yarn width, which may be important depending on the final

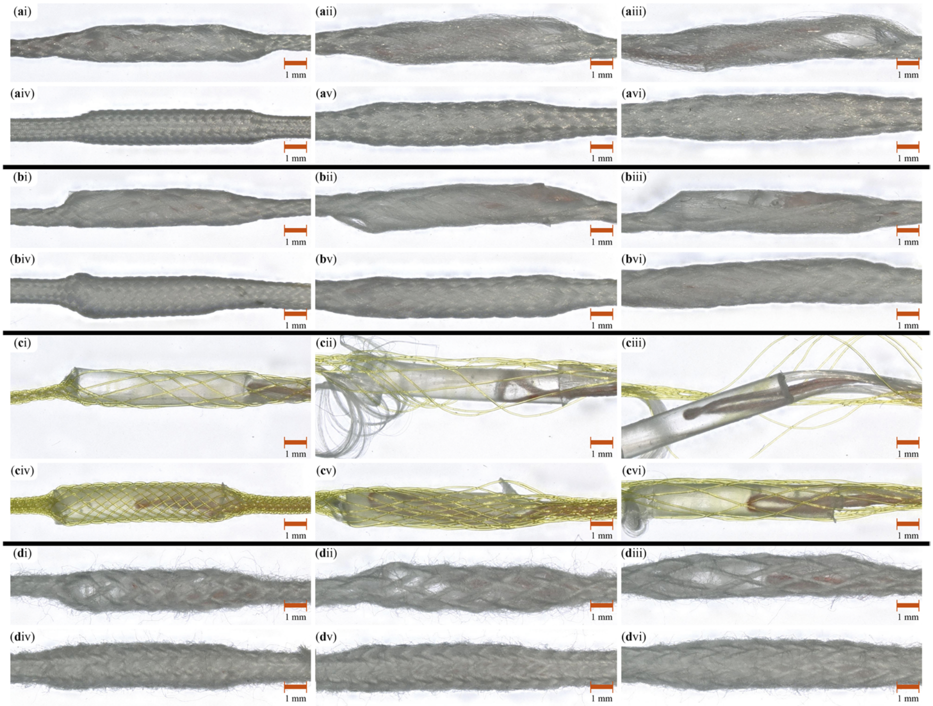

Figure 3. Example microscope images of cylindrical micro-pods (1.5 mm diameter) covered in a braid. (a) Polyester. (b) Nylon. (c) Monofilament. (d) Cotton. (i) 12 yarn carriers, 5 mm lay length. (ii) 12 yarn carriers, 10 mm lay length. (iii) 12 yarn carriers, 15 mm lay length. (iv) 24 yarn carriers, 5 mm lay length. (v) 24 yarn carriers, 10 mm lay length. (vi) 24 yarn carriers, 15 mm lay length.

application. The use of less carrier yarns can provide a uniform structure that is less densely covered in fibres (Figure 3(ai)), which may be desirable for some applications, such as those involving light. The use of 12 yarn carriers and a longer lay length however yielded poor covering results (Figure 3(aiii)).

Figure 3(b–d) provide examples of micro-pods covered with nylon (2/78/68 from ContiFibre S.p.A., Tobagi, Italy), monofilament (1/24 combed cotton from Yeoman Yarns, Leicester, UK), and cotton (0.2 mm diameter, Type: NYB020SS) respectively.

The most uniform coverage was observed for nylon when 24 yarn carriers and a 10 mm lay length where used, however generally the coverage was similar to what was observed using polyester.

Braiding using a monofilament provided very poor results when 12 carriers and a long lay length was used (Figure 3(cii,ciii)). Otherwise a relatively good coverage could be achieved.

While all of the parameters led to good coverage when cotton was used as the braiding material, frequent breakages were encountered when forming the braid. This was due to the high levels of tension applied to the yarns during the braiding process and cotton's lower tensile strength compared to synthetic materials.

Braiding parameters would also need to be optimised for different geometries of micro-pod, with both the size and shape influencing the level of coverage. The short study below explored the key braiding parameters for a small, cuboid pod. As this micro-pod was larger than the pod above, 24 yarn carriers were used for all of these experiments. Additionally, to achieve a good braid, the lay length had to be optimised differently before and after the micro-pod, compared to the micro-pod position. Only polyester and nylon were investigated in this study. In addition to optimising the lay length, different linear densities for the carrier yarns were investigated to ensure a good coverage was achieved (Figure 4).

For this micro-pod design, the polyester braid with a lower linear density and 8 mm lay length at the micro-pod, as well as the nylon braid with a 9 mm lay length for the entire braid provided poor coverage (Figure 4(a,f)). The other braids provided a good coverage, however the other nylon braids both produced relatively rigid final yarns, which was undesirable for applications where the yarn would be worn close to the skin. The polyester (2 × 1/167/36) braid, where a 9 mm lay length was used over the micro-pod, gave the best coverage and a highly flexible yarn (Figure 4(c)).

Copper interconnections

Another identified challenge with the E-yarn design was related to the restriction brought about by using a multistranded bare copper wire for the electrical interconnections. Three distinct issues were identified.

Firstly, using bare copper wire (that was not insulated) meant that circuits had to be wired in series. As shown in the work by Hardy et al. (Hardy et al.

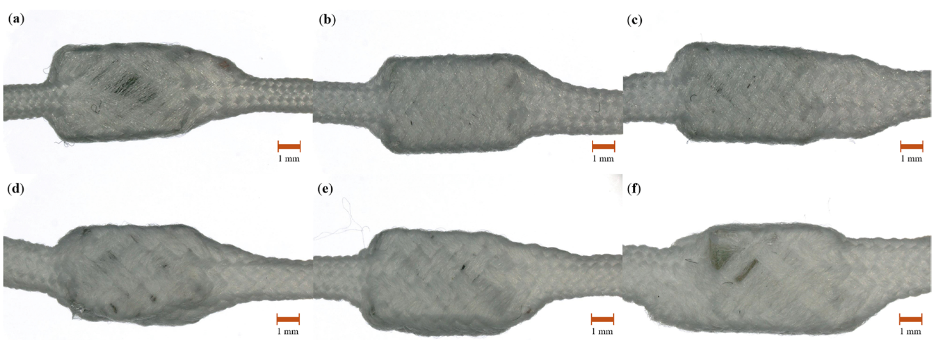

Figure 4. A selection of example microscope images of a cuboid micro-pod covered in a braid. (a) Polyester (1 × 1/167/48), 8 mm lay length at component, 5 mm after component. (b) Polyester (2 × 1/167/36), 12 mm lay length at component, 6 mm after component. (c) Polyester (2 × 1/167/36), 9 mm lay length at component, 6 mm after component. (d) Nylon (2 × 2/78/68), 6 mm lay length at component, 5 mm after component. (e) Nylon (2 × 2/78/68), 9 mm lay length at component, 5 mm after component. (f) Nylon (2 × 2/78/68), 9 mm lay length at component, 9 mm after component.

2018), when creating a garment with multiple LEDs, wiring these in series meant that relatively high voltages were needed to power the circuit (in this case, 24V); this created complications in the control circuitry. By soldering active components, such as LEDs, in parallel, much lower voltages (~2V) are required. This design also caused problems when incorporating the yarns into textiles. As the components were soldered in series, one end of the E-yarn acted as a positive terminal and one the negative meaning that the wiring of the yarn had to bring both ends back to any supporting hardware module. This complicated design choices for the textile and risked putting the yarns under additional mechanical stress when in use as the yarn would have to be mechanically fixed at both ends. In cases where soldering multiple components in parallel was needed, such as for the miniature solar panels shown in (Satharasinghe, Hughes-Riley, and Dias 2020), the non-insulated wire restricted the design choices for the miniature solar panel spacing. Positioning the panels too far apart would mean that the copper wires had more freedom of movement to touch and short-circuit. This meant that the panels had to be very closely spaced together. An additional issue emerged when complex components requiring many electrical terminals (like accelerometers) were used. In these cases some electrical interconnections would have to travel near each other, leading to shorting across the wires; so wires would need to be covered to prevent them from touching.

Wire breakages were also known to occur, such as during washing. Wash durability is a key feature for electronic textile garments and products that will be held close to the skin. As most of the applications identified for E-yarn technology were health and wellbeing related, requiring close body contact, wash durability would be essential. Therefore a wash durability study using machine washing was conducted where it was observed that the primary point-of-failure during washing was the copper wire breaking (Hardy, Rahemtulla, et al. 2020). This was particularly prevalent at the micro-pod interface where large bending and twisting motions would lead to wire failure.

Finally, using a non-insulated wire led to failure in the function of the E-yarns under certain conditions. This was evidenced in a trial with a temperature-sensing cycling suit where excessive sweat build-up led to erroneous temperature readings, as the conductive sweat was creating a parallel conductive pathway around the thermistor (Hughes-Riley et al. 2021). This issue was examined in the paper and it was seen that it could be mitigated by using an insulated wire in the E-yarns construction instead of the multi-strand copper wire.

A multi-strand Litz wire (BXL2001, OSCO Ltd., Milton Keynes, UK) was selected for constructing future E-yarns. This wire comprised of copper strands coated in an enamel to prevent short-circuiting and protect the conductor from liquids, the enamel-coated conductive multi-strand wires were further protected by a Nylon covering yarn. This structure resulted in a wire that was highly flexible and possessed many yarn-like qualities. E-yarns constructed with Litz wire were shown to not fail in highly saline environments (Hughes-Riley et al. 2021).

Revised E-yarn design

A new E-yarn design to resolve these identified challenges was therefore realised. Using contact soldering, the new E-yarn design first saw the component soldered onto the thin Litz wire (Figure 5(a)): This was achieved using a hot soldering iron. Initially, a small amount of solder was used to strip off the insulative covering on a small section of the Litz wire. The wire was then placed on the component, and the soldering iron was briefly pressed onto the solder pad to create the electrical connection. An example of this type of solder joint is shown in Figure 5(c). The shiny outer layer shows that a good solder joint has been made. It was observed that, generally, this connection was more mechanically robust than when using reflow soldering, meaning that small mechanical stresses on the joint were less likely to lead to breakages. This would make handling the components easier (either by hand or using automated processes) when moving onto the later processing steps. An example of a solder joint from a component soldered using reflow soldering is shown in Figure 5(b). The uneven surface is an indication of a poor solder joint and was common when using this method. It should be noted however that reflow soldering could be used to attach Litz wire to components, as shown in the literature (Satharasinghe, Hughes-Riley, and Dias 2020).

Schematics of the E-yarn production process for a typical E-yarn are shown in Figure 6.

The soldered component would then be encapsulated. Different micro-pod designs and geometries have been explored for different component shapes, with a tubular shape typically being used for components such as thermistors (Hughes-Riley et al. 2017). Cuboid micro-pods have been used for some larger components, such as inertial measurement units (IMUs) (Rahemtulla et al. 2023), to both minimise the final yarn's size and to also aid in the correct positioning of the component in the textile. This was particularly important for the embedded IMUs, as knowing the orientation of the sensor is vital

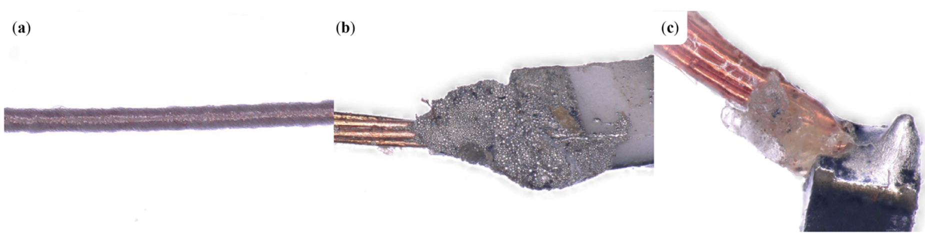

Figure 5. (a) An image of a Litz wire. (b) A component soldered onto a multi-strand copper wire using reflow soldering. (c) A component soldered onto a Litz wire using a soldering process.

for understanding the readings. During the encapsulation process a supporting yarn or yarns are typically introduced inside of the micro-pod: this is either a single Vectran yarn (for example, Rahemtulla et al. 2023) or multiple multi-strand polyester yarns (as shown in Marasinghe et al. 2024). This adds strength to the E-yarn and can help give the E-yarns a consistent appearance, as without these extra yarns the component's location is significantly larger than the rest of the yarn. The micro-pods are formed using a UV-curable resin as before. Figure 6(b) shows a schematic of a typical micro-pod geometry.

The soldered and encapsulated component, along with the supporting yarns and wires, were finally covered using a conventional braid constructed using a suture braiding machine (RU1/24-80, Herzog GmbH, Oldenburg, Germany). Polyester is generally used and has been found to give a good level of coverage as discussed above (see Figure 3(a)). Figure 6(c) shows a schematic of a typical E-yarn constructed using this technique, while Figure 6(d) shows an image of a completed E-yarn of this type.

The revised E-yarn design detailed in this work can also be applied to other E-yarn types. Figure 7 shows a comparison of an older accelerometer embedded E-yarn (at the encapsulation stage), compared to a revised design.

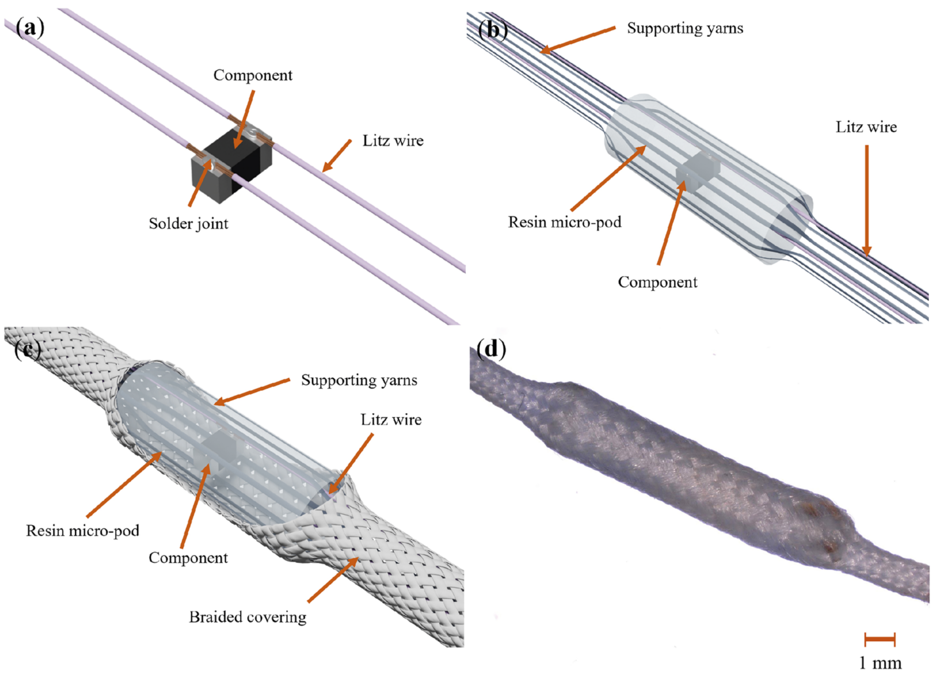

Figure 6. (a) Schematic of a component, such as a thermistor, soldered onto Litz wires. (b) Schematic of a thermistor soldered onto Litz wires and encapsulated along with supporting yarns. (c) Schematic representation of the interior of a typical completed E-yarn. (d) Microscope image of a typical completed E-yarn.

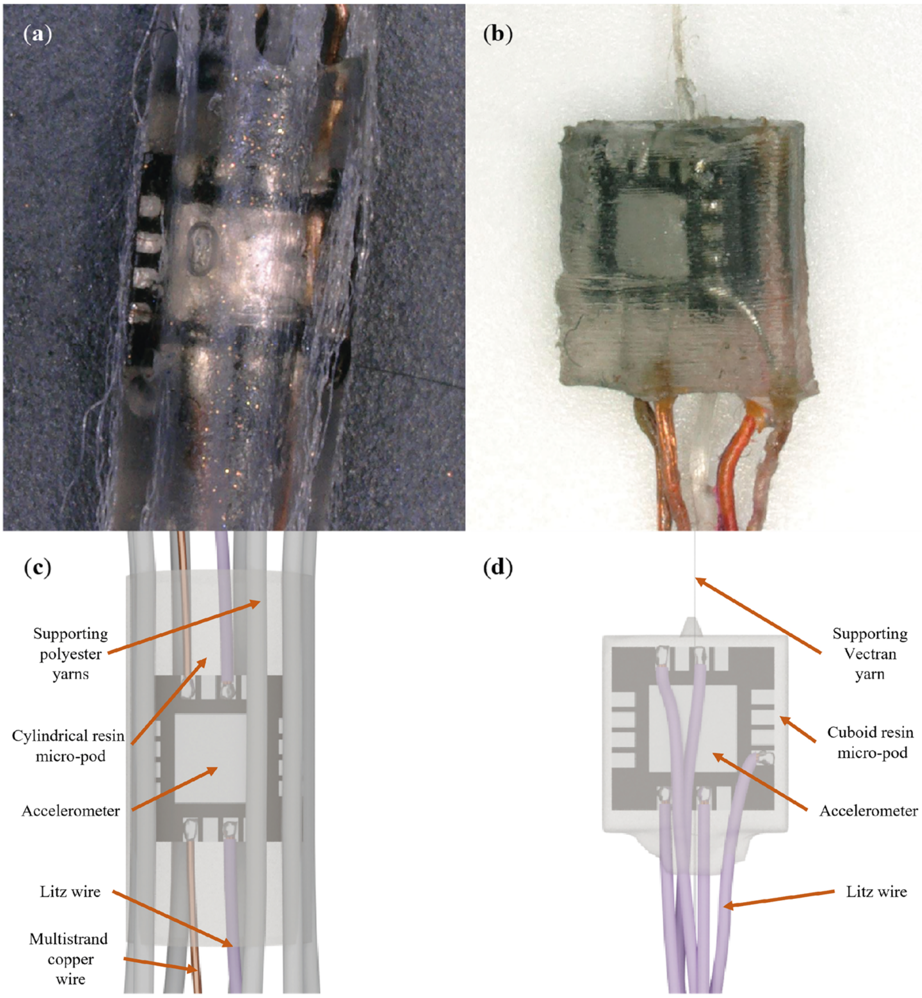

Figure 7. Images of accelerometer embedded electronic yarns (at the encapsulation stage). (a) An accelerometer embedded electronic yarn design from the literature (Rahemtulla, Hughes-Riley, and Dias 2019). (b) An accelerometer embedded electronic yarn design created using concepts described in this work. (c) Schematic of the design shown in (a). (d) Schematic of the design shown in (b).

Figure 7(a) shows an earlier design of accelerometer embedded E-yarn (developed for vibration sensing). Here a combination of Litz wire and multistrand copper wires were used and soldered onto the device using IR reflow soldering. The literature highlights the difficulty in reliably soldering the *y*-axis terminal (Rahemtulla, Hughes-Riley, and Dias 2019). By using a contact soldering method, and only Litz wires, all of the accelerometer terminals could be easily soldered (Figure 7(b)). The new design utilises a cuboid micro-pod shape, which would facilitate easier positioning of the sensor. This is important as the correct orientation of the device is essential for accurate function.

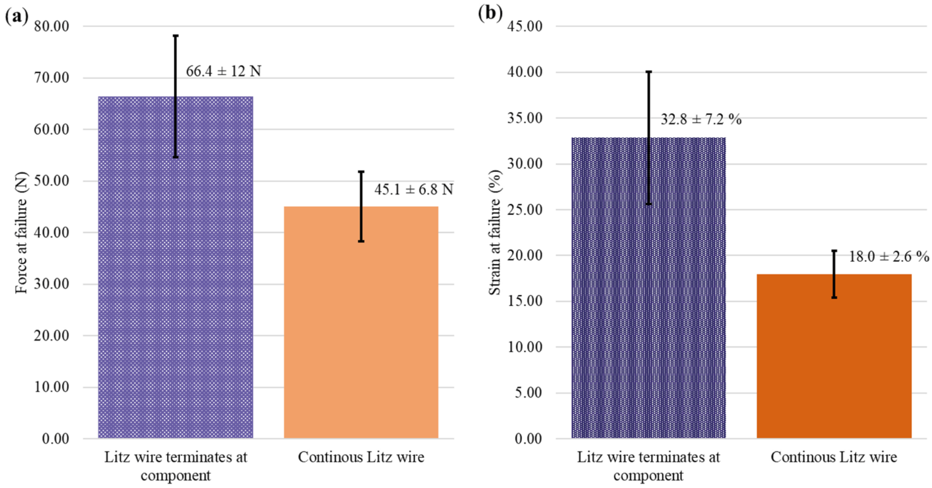

Figure 8. Ultimate tensile strength of E-yarns. Two designs have been explored. All data represents five repeat tests. (a) Force at failure. (b) Strain at failure.

The final E-yarn is robust, and the ultimate tensile strength has been characterised using textile test standards (in this case ASTM D2256/D 2010 'Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method'; a gauge length of 50 mm and a speed of 50 mm/min were used) and a Zwick/Roell Z2.5 tensile testing machine (Zwick/Roell GmbH & Co. KG, Ulm, Germany). The test data below investigates E-yarns with embedded resistors (with a similar design to a light emitting or temperature sensing E-yarn) where two scenarios are explored: where the Litz wire runs the length of the entire yarn (which would be needed in a yarn with multiple components) and where the Litz wire terminates at the component (which is the common configuration for sensing E-yarns, where normally only one sensor would be in each yarn, for example IMU embedded E-yarns, (Rahemtulla et al. 2023)) (Figure 8).

The resultant yarns are capable of withstanding significant tensile forces. When compared to earlier E-yarn designs discussed in this work, the ultimate tensile strength of the new design is slightly less; for example (Hardy, Anastasopoulos, et al. 2020) reported tensile strengths of 98–111 N. The strength of the older design could be attributed to the knit-braid structure, the inclusion of Vectran as a supporting yarn, or the twisting of the copper wire which was employed in some work. Ultimately the reported tensile strength of this new E-yarn should be sufficient for most wearable applications. It is believed that the flexible nature of the Litz wire now used will make the E-yarns more robust to the twisting and bending that occur during machine washing.

Discussion and future prospects

Knowledge regarding the limitations of the earlier E-yarn design and the new design created to overcome these issues has been implemented in a number of studies including the creation of large textile solar panels (Abeywickrama et al. 2023) (in this case, the large panel did not use an outer braided covering). A motion sensing sock for gait monitoring to aid in rehabilitation (Lugoda et al. 2022) has been developed and has undergone in-lab trials with humans. A different motion-sensing E-yarn was developed to create a fall and near-fall detecting over-sock for use by older adults (Rahemtulla et al. 2023), which has also undergone trials with healthy participants. It is envisioned that such a device could be used to aid in fall risk assessments for older adults in the future.

This new E-yarn design is also currently being used for studies with humans for understanding sports performance. A vest with embedded temperature sensing elements for understanding thermoregulation during exercise was recently created and tested with a human subject (Marasinghe et al. 2024). A glove with pulse rate monitoring capabilities was also created using this new design of E-yarn, in this case LEDs and optical sensors were embedded within yarns. The devices was validated with ten health subjects (Peiris et al. 2024). The new E-yarn design is currently undergoing rigorous testing to help understand the boundary conditions for its use and identify potential points of weakness.

A key issue that has hindered the commercial adoptions for many electronic textile products is a lack of wash durability, which is critical for textiles that are intended to be incorporated into worn garments or textiles that will be close to the body (such as blankets). For a consumer ease of care is important and being able to clean E-textiles using standard machine washing is desirable. It is known that the earlier iteration of the E-yarn technology (the design shown in Figure 1) experienced some failures during machine washing and drying trials (Hardy, Rahemtulla, et al. 2020) primarily due to failure in the copper wire. Failures occurred at relatively low numbers of washing cycles, for example E-yarns containing a pair of LEDs started failing between 5 and 10 washes. Preliminary results from a comprehensive wash durability study conducted using the new E-yarn design have shown significantly enhanced wash durability, with a high percentage of E-yarns surviving 25 washing wash cycles, making the improved E-yarn design more appropriate for consumer applications.

By creating a robust E-yarn that addresses the limitations identified over years of prototyping and testing, the design brings the technology one step closer to becoming a product that can be scaled-up and commercialized. However, there are challenges in manufacturing the E-yarn design presented in this work at a large scale. The use of Litz wire introduces an additional cleaning step in the manufacturing process, which will slow the overall process down. Further, braiding is not a fast process and alternative covering methods may need to be explored if high volumes of E-yarns are required.

The E-yarn concept discussed in this work opens exciting new prospects for this technology. With the possibility of embedding complex, multi-terminal devices into yarns, a plethora of new potential physiological sensors are available. Further, the new yarn design can easily facilitate the construction of circuits within the yarn. The recently developed temperature sensing vest incorporated the voltage divider circuit within the yarn itself (Marasinghe et al. 2024). Further E-yarn design may see the incorporation of more complex circuitry in the future.

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Notes on contributors

Arash M. Shahidi is a Senior Research Fellow in Technical and Medical Textiles in the Nottingham School of Art and Design at Nottingham Trent University, UK. He is an active member of the Advanced Textiles Research Group at Nottingham Trent University. Dr Arash Shahidi's current research is highly multidisciplinary and is focussed on characterising advanced textile structures for medical and industrial applications, flexural composites, and electronic textiles.

Kalana Marasinghe is a Research Fellow in Electronic Yarns in the Advanced Textiles Research Group at Nottingham Trent University. He graduated from King's College London with his BEng in Mechanical Engineering in 2012 and proceeded to University College London for his Master of Science degree in Mechanical Engineering.

Parvin Ebrahimi is a second-year doctoral candidate specializing in solar electronic textiles, focusing on characterization, optimization, and power management. She has developed this new textile solar panel as part of her research. She is a member of the Advanced Textiles Research Group at Nottingham Trent University, United Kingdom.

Carlos Oliveira is an Experimental Officer in the Nottingham School of Art and Design at Nottingham Trent University, UK, as well as an active member of the Advanced Textiles Research Group. He is an expert in knitting.

Nishadi Perera is a final year doctoral candidate in the Nottingham School of Art and Design at Nottingham Trent University, UK. She has a background in textile process engineering and has over five years of experience working in technical textiles and open innovation.

Amanda Briggs-Goode is a Professor and the Head of Department for Fashion, Textiles and Knitwear Design in the Nottingham School of Art and Design at Nottingham Trent University, UK. In this role Amanda provides subject leadership and management for a staff team of 30+, which includes the Advanced Textiles Research Group.

Tilak Dias is an Emeritus Professor at Nottingham Trent University. Tilak has given 60 invited talks and has over 170 scientific papers in leading journals and conferences. His research focuses on the development of electronic textiles and advanced knitting technologies.

Theo Hughes-Riley is an Associate Professor in Electronic Textiles. Dr Hughes-Riley has a growing international reputation in the area of E-textiles as demonstrated by invitations to speak at various relevant international conferences, and has secured £2M of research funding as an investigator in this field. Dr Hughes-Riley has authored over 60 publications, including over 40 peer-reviewed journal articles, primarily in the fields of E-textiles, and sensors.

ORCID

Arash M. Shahidi http://orcid.org/0000-0002-7780-3122
Kalana Marasinghe http://orcid.org/0000-0001-9050-5261
Parvin Ebrahimi http://orcid.org/0009-0003-2088-6857
Carlos Oliveira http://orcid.org/0000-0001-8143-3534
Amanda Briggs-Goode http://orcid.org/0000-0002-5194-1009

Tilak Dias http://orcid.org/0000-0002-3533-0398
Theo Hughes-Riley http://orcid.org/0000-0001-8020-430X

Data availability statement

The data used for this work can be found on Figshare at https://doi.org/10.6084/m9.figshare.26371015. The data archive also includes further microscope images of electronic yarn braiding trials and the raw force against strain curves collected when analysing the ultimate tensile strength of the yarns.

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