fibers

MDPI

Article

Engineering a Costume for Performance Using Illuminated LED-Yarns

Dorothy A. Hardy *, Andrea Moneta, Viktorija Sakalyte †, Lauren Connolly ‡, Arash Shahidi and Theodore Hughes-Riley

School of Art and Design, Nottingham Trent University, Shakespeare Street, Nottingham NG1 4FQ, UK; andrea.moneta@ntu.ac.uk (A.M.); viktorija.sakalyte@hud.ac.uk (V.S.); Lauren_Connolly18@hotmail.co.uk (L.C.); arash.shahidi@ntu.ac.uk (A.S.); theodore.hughesriley@ntu.ac.uk (T.H.-R.)

* Correspondence: dorothy.hardy@ntu.ac.uk; Tel.: +44-115-84-82709

† Current address: School of Art, Design and Architecture, University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK.

‡ Ms. Connolly is now a Freelance Theatre Designer.

Received: 30 April 2018; Accepted: 29 May 2018; Published: 1 June 2018

Abstract: A goal in the field of wearable technology is to blend electronics with textile fibers to create garments that drape and conform as normal, with additional functionality provided by the embedded electronics. This can be achieved with electronic yarns (E-yarns), in which electronics are integrated within the fibers of a yarn. A challenge is incorporating non-stretch E-yarns with stretch fabric that is desirable for some applications. To address this challenge, E-yarns containing LEDs were embroidered onto the stretch fabric of a unitard used as part of a carnival costume. A zig-zag pattern of attachment of E-yarns was developed. Tensile testing showed this pattern was successful in preventing breakages within the E-yarns. Use in performance demonstrated that a dancer was unimpeded by the presence of the E-yarns within the unitard, but also a weakness in the junctions between E-yarns was observed, requiring further design work and reinforcement. The level of visibility of the chosen red LEDs within black E-yarns was low. The project demonstrated the feasibility of using E-yarns with stretch fabrics. This will be particularly useful in applications where E-yarns containing sensors are required in close contact with skin to provide meaningful on-body readings, without impeding the wearer.

Keywords: electronic yarn; E-yarn; LED-yarn; LED; stretch fabric; illuminated textiles; electronic textiles; E-textiles

1. Introduction

Incorporation of electronics within textiles offers an opportunity to integrate lighting into clothing and to monitor health through sensors embedded within clothing. The growing market for electronic textiles (E-textiles) demonstrates the high level of interest in this areas [1]. Thus, the need exists for further development of nonintrusive electronics that do not impede the wearer. Ideally, clothing incorporating electronics would have normal drape, conformability, and stretch. This is a challenge due to the considerable difference in material properties between textile fibers and electronics. One solution is to use electronic yarn (E-yarn) [2], which omits the circuit board substrate that forms a part of many electronic circuits. Instead, package dyes are attached onto a flexible copper wire to create what is effectively an electronic fiber, which is then contained within textile fibers. This creates an E-yarn with a textile feel and drape similar to that of other fibers within garments [3]. Development of a semi-automated process has led to the ability to produce E-yarns relatively easily and quickly [4]. Previously, E-yarns had been produced by a craft process [5], with six or fewer being used in most garments [6]. There was a need to demonstrate the feasibility of attaching tens of E-yarns onto one garment, illustrating how electronics could become a significant and integral part of clothing. Finding a method of attaching E-yarns to stretch fabric is also important. E-yarns are non-stretch due to the central, non-stretch copper wire, but integration with stretch fabrics would enable the use of sensors within E-yarns to take measurements of the human body from as close to the skin surface as possible. This would be especially useful in obtaining meaningful readings from sensors included within E-yarns by increasing the number and type of garments into which this technology could usefully be incorporated.

E-yarns are designed to be unobtrusive within textiles. In the project described in this paper, we investigated the use of the E-yarns in stretch fabrics and tested their functionality. This was achieved through use of E-yarns containing LEDs (LED-yarns), as shown in Figure 1. The illumination of the LEDs enabled the quick assessment of the functionality of the E-yarns. The chosen project was the design of an illuminated carnival costume for use in a competition to be held in a theatre [7]. This provided a time-delimited project for which funding was available, so that a garment containing multiple LED-yarns could be designed and made. This provided an ideal platform for testing methods of attaching LED-yarns onto stretch fabric that was placed next to the skin of a dancer wearing the costume. This provided a rigorous test of the durability of the E-yarns and their connections in a relevant operational environment, so that any subsequent recommendations for the use of E-yarn on stretch fabric could be considered with this as a benchmark. Displaying the costume in carnivals and other performances could achieve an additional aim of ensuring that the E-yarns were viewed by a large audience, increasing the visibility of this technology.

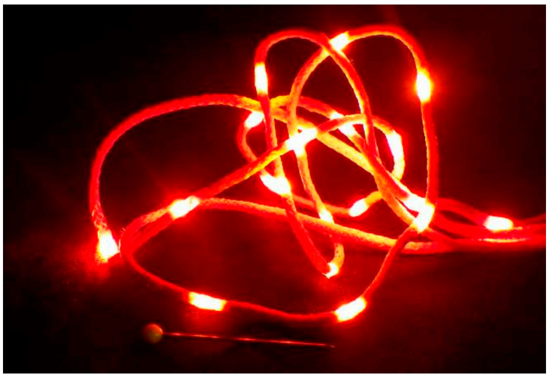

Figure 1. Illuminated light emitting diode (LED)-yarn shown next to a 30 mm long pin.

The initial brief for the project required the use of illuminated E-yarns, other methods for incorporating E-textile lighting exist and have been gradually developed [8,9]. The earliest example is the lighting worn by dancers in the ballet La Farandole in 1884 [10], showing use of filament lightbulbs in costume lighting applications. Electronic textiles for lighting typically use one of four main methods: fiber optics [11,12], LED strips [13], electroluminescent wires [14], and lasers [15]. Electroluminescent wires, fiber optics, and the use of lasers generate sufficient light to be clearly visible during theatre or outdoor night-time performances, but also restrict the flexibility and conformability of a garment. Similarly, the direct attachment of LEDs onto a costume using strips of LEDs or sewing individual LEDs into holders is non-ideal as it affects the textile material properties. Examples of costumes incorporating these elements include Bono's "laser suit" [16], and the Slovakian Tron Dance that incorporate LED-covered suits [13]. Fiber optics have been included within costumes that can accommodate the limited flexibility of the fiber optic elements, such as the Scottish Opera's Queen of the Night costume [12]. The lack of flexibility and conformity has limited the use of E-textiles within performance. Wider adoption of E-textiles has also likely been limited in part by cost and by the infancy of design philosophies and practices when using E-textiles [17].

Smaller and cheaper microelectronics have allowed some electronic garments and wearable accessories to enter the marketplace, with aesthetics being the primary function. These have principally been featured in the clubbing scene, with an example being the Sound Activated T-shirt [18]. High-end alternatives also exist, such as the K-Dress from CuteCircuit, which contains LEDs [19]. The formation of companies focused on using electronic textiles as a craft skill to create bespoke garments has also resulted in a more general adoption of E-textile technology [20]. LED-yarns were used in the research described in this paper. This was a development on the history of inclusion of lighting within costumes for use in performance.

The aim of this research was to demonstrate the feasibility of attaching multiple LED E-yarns onto a stretch garment for use in performance. This showed the viability of fabricating clothing containing many electronic components held close to the skin of the wearer without impeding the wearer's ability to dance. Details are provided of a zig-zag E-yarn shape developed to accommodate the non-stretch E-yarn on stretch fabric. The design of the junctions between the E-yarns was found to be important, and development of these is discussed.

2. Materials and Methods

The choice of a carnival costume and competition, plus the aims described above, created a framework for the design process. The costume design focused around the use of E-yarns, with the method of attachment of numerous E-yarns onto the costume being key. The carnival "King" competition, and subsequent carnivals in which the costume was displayed, required large, eye-catching costumes in which a dancer can move fluidly, unrestricted by weight or bulk. For this large-scale carnival costume, much of the dancer's body would be covered, so that fabric next to the skin could not easily be seen in many areas of the costume. The LED-yarns were therefore included within the legs of the costume, as the legs would be moving and simultaneously visible to the audience during dancing.

The carnival costume involved two distinct parts: a unitard onto which the E-yarns were embroidered, and a frame worn by a dancer, to which many of the other parts of the costume were attached. The incorporation of LED-yarn into the legs of the costume was the focus of the research described in this paper. A decision was made to use a unitard onto which the LED-yarns would be attached as this provided a skin-tight, stretch platform for attachment of the LED-yarns. A black stretch unitard was chosen (Capezio® Men's Footless Tank Unitard in Black, Capezio®, Norwich, UK). Placing the LED-yarns on the legs of the costume ensured that they were visible and subjected to movement during dancing, testing the ability of the E-yarn to withstand movement while attached to a stretch fabric. A flame theme was chosen for the costume, providing the opportunity to use curved and illuminated flame-like patterns. The chosen pattern contained E-yarns in horizontal bands around the unitard legs, with interconnecting LED-yarns between parallel E-yarns that were connected to a battery in a pocket on the back of the unitard. The E-yarn was non-stretch due to the central strand of conductive copper within. A curving pattern was chosen for the E-yarns to allow the underlying fabric to stretch without breaking the E-yarn.

2.1. E-Yarn Attachment to Stretch Fabric

Initial test attachments of the E-yarn to stretch fabric were performed by hand, using a blind stitch (Figure 2a). The initial zig-zag design was slightly less controlled, but a zig-zag pattern with a more ordered structure was chosen for the final design as we believed that this would be easier to implement using an embroidery machine. We assumed that machine embroidery would form a strong attachment between E-yarns and fabric to withstand the stretch and movement of the fabric during performance. A sewing machine (Bernina 1000 Special, Steckborn, Switzerland) was used, with the E-yarn fed through a cording foot to create a wide zig-zag stitch to keep the yarn in place on the fabric surface. Figure 2b shows a sample of the stretch fabric with E-yarns machine embroidered into place in the chosen zig-zag pattern.

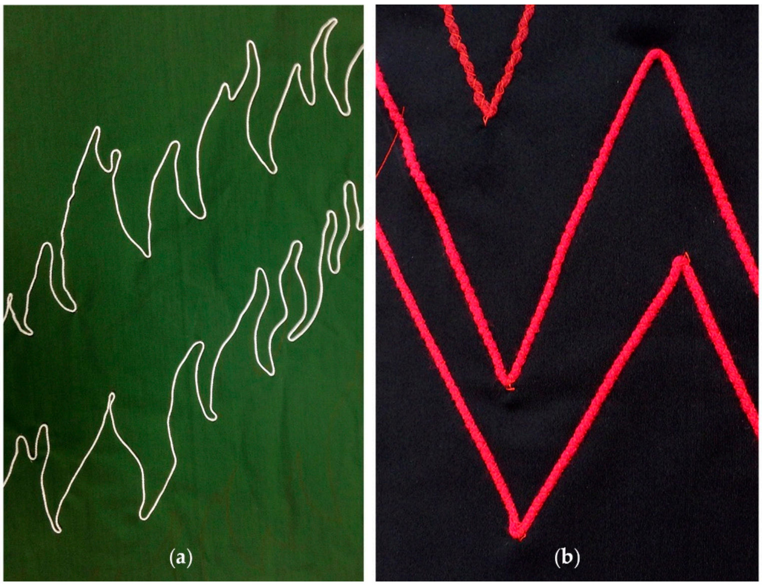

Figure 2. Zig-zag attachment pattern of electronic yarns (E-yarns) to stretch fabric: (**a**) Initial design, and (**b**) Final, more-ordered design.

2.2. Connecting E-Yarns

Connections between E-yarns, and between E-yarns and LED-yarns, were required to create an electrical circuit on the surface of the unitard. These were created by twisting together the copper wires protruding from the end of each E-yarn. These connections were then soldered together. Dymax 9001-E-V3.5 resin (Dymax Corporation, Torrington, CT, USA) was used to cover and reinforce the soldered joints. This was cured under UV light for 180 s using a Dymax Bluewave 50 Light Curing System (Dymax Corporation, Torrington, CT, USA). The connections were manually stitched into place on the fabric surface using a satin stitch to provide protection from external abrasion.

2.3. Tensile Testing of the E-Yarn Attachment to Stretch Fabric

Tensile testing was used to determine whether the curved pattern of the E-yarn attachment to the fabric surface was sufficient to prevent E-yarn breakage. Samples of stretch fabric (210 × 60 mm) were cut from a unitard identical to the one used to make the costume. Four of each sample were made, with the E-yarn embroidered onto the surface of the fabric in the following pattern:

- In a straight line.
- In a curved pattern.
- In a curved pattern, with a connection between the two E-yarns used to create the pattern.

The testing standard ASTM E8 [21] was the basis for tests on a zwickiLine tensile tester (Z2.5, Zwick/Roell, Ulm, Germany), using six testing cycles with a 30 s hold on the last cycle. The samples were taken to 50% strain, which was assumed to exceed the level of stretch to be experienced by the unitard to which E-yarns were attached. At this strain, the fabric was permanently damaged. Continuity testing was performed on each sample before and after tensile testing to find if the central conductive element of the E-yarn remained intact.

2.4. Circuitry

A circuit was required to power the LED-yarns. This is shown in the diagram in Figure 3. The periphery of the diagram shows long lengths of black E-yarn connected to a lithium polymer battery. Short lengths of LED-yarn were connected in parallel into this main circuit. The diagram shows connections to two lengths of LED-yarn, each containing 12 LEDs. Each LED (KPHHS-1005SURCK, Kingbright, Taipei, Taiwan) required 2 V, so each section containing 12 LEDs required 24 V to be supplied by the battery. The LED-yarns were connected to short lengths of red E-yarn that added colorful detail to the costume. These E-yarns were then connected to the black E-yarns of the main circuit that ran down the outside of the costume legs.

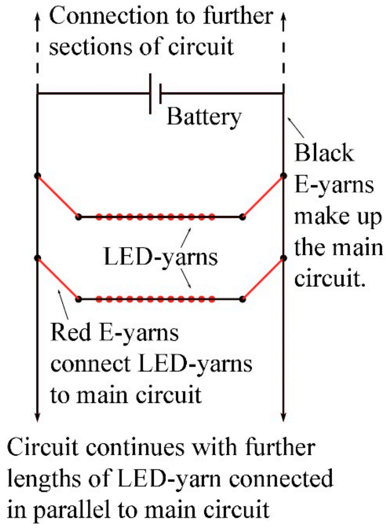

Figure 3. Diagram showing part of the circuitry attached to the costume: LED-yarns, each containing 12 LEDs attached in parallel between black E-yarns that form the main circuit on the costume. Red E-yarns connect the LED-yarns to this main circuit that is connected to a battery.

A section of the fabricated circuit is shown in Figure 4. This shows the zig-zag attachment pattern of the E-yarns and LED-yarns. A section of black LED-yarn containing 12 LEDs is highlighted in yellow. Each end of this highlighted LED-yarn was connected to a red E-yarn. The red E-yarns were placed above and below the LED-yarn to form a pattern on the costume. Three zig-zag lines of LEDs were included on the front of the costume legs. Ultimately, 144 LEDs were used, with two lengths of LED-yarn each containing 12 LEDs, placed at three levels on each leg.

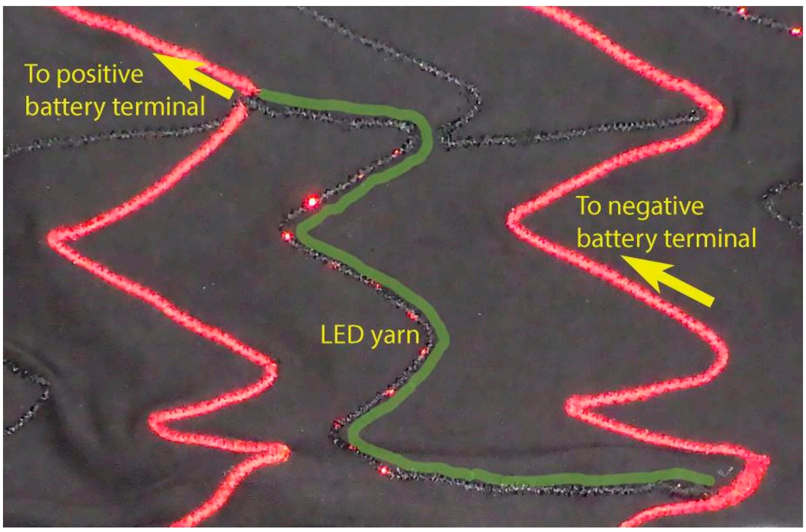

Figure 4. Circuitry on the costume: The LED-yarn is highlighted in green. Each LED-yarn contained 12 LEDs and was connected to two red E-yarns: One red E-yarn was connected to the positive terminal of a battery, and the other to the negative terminal.

The circuit was designed to incorporate the LED-yarns, with additional E-yarns connecting these to a battery placed on the center back of the unitard. The circuit was fabricated by placing the unitard on a mannequin to ensure that the costume legs would conform to the dancer's legs once the E-yarn was embroidered onto the fabric surface. Having placed the E-yarns in the desired positions, the circuit was created. Each positive and negative end of LED-yarn was connected to the E-yarns that were connected to the positive and negative battery terminals. The connections were soldered, coated with resin, and then embroidered into place as described in Section 2.2. The remaining lengths of E-yarn were machine stitched onto the unitard fabric using a zig-zag stitch. The machine sewing process proved to be too harsh, with almost half of the connections between the E-yarns breaking during the process. The broken connections were re-soldered and covered with resin. Sweat would possibly impact the performance of the E-yarns, causing conduction of electricity away from the lighting circuit. A resistor was included within the electrical circuit to ensure that no large power leakages could be experienced by the dancer. No current leakage was experienced by the dancer, but recommendations for further costume designs include use of insulated copper wire to minimise the possibility of current leakage.

2.5. Costume Frame

A carnival "King" costume must fill a large area to create an impact in competition and in parades [22], so the unitard with attached LED-yarns was worn underneath a backpack or frame, as shown in Figure 5. This was an aluminum structure to which rods were attached that held wings, flame shapes, extra LED lighting, and a "tail" of flexible rods. These radiated out from the center of the costume. The frame was made by an artisan specializing in large scale costume design [23]. Despite the costume size, the weight was reduced to a minimum through use of light, yet resilient, materials within and attached to the frame: composite rods, aluminum, lightweight fabrics, and foam sheet. The backpack was designed to make allowances for the placement of E-yarns and battery packs on the costume, without interfering with the LEDs' performance within the E-yarns, or with the electrical connections.

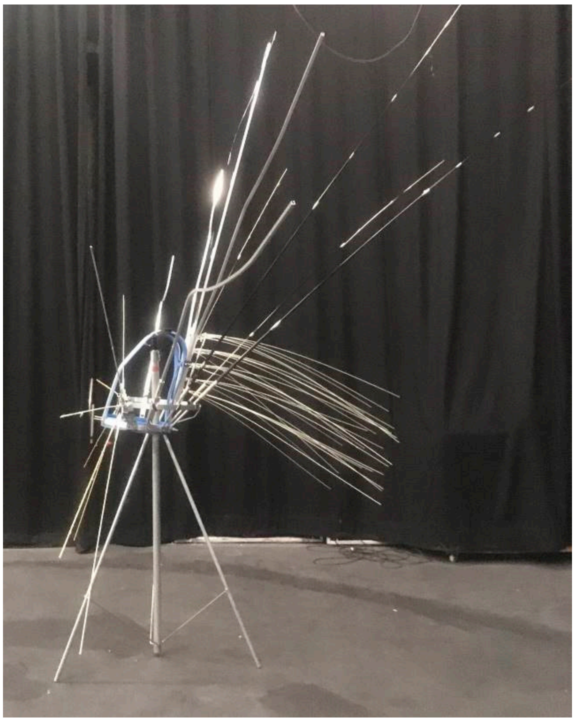

Figure 5. Completed frame to be worn over the unitard. The frame is shown supported on a stand.

3. Results

The carnival costume was successfully displayed in competition. The final costume design is shown in Figure 6a, with a detail of the illumination from the LED-yarns on the leggings in Figure 6b. A central design aim was to ensure that the performer was able to move and dance unimpeded and with confidence. This was achieved as the flexibility of the costume elements, including the E-yarns, allowed the whole costume to move smoothly as part of the choreography. Another design intention was that the LED-yarns should be visible. The level of illumination from the red LEDs on the unitard was minimal, with not all of the lines of the 12 LEDs illuminating. The E-yarns formed a very subtle detail amongst the overall impact of the costume, with higher levels of illumination from LED strips along the costume wings dominating.

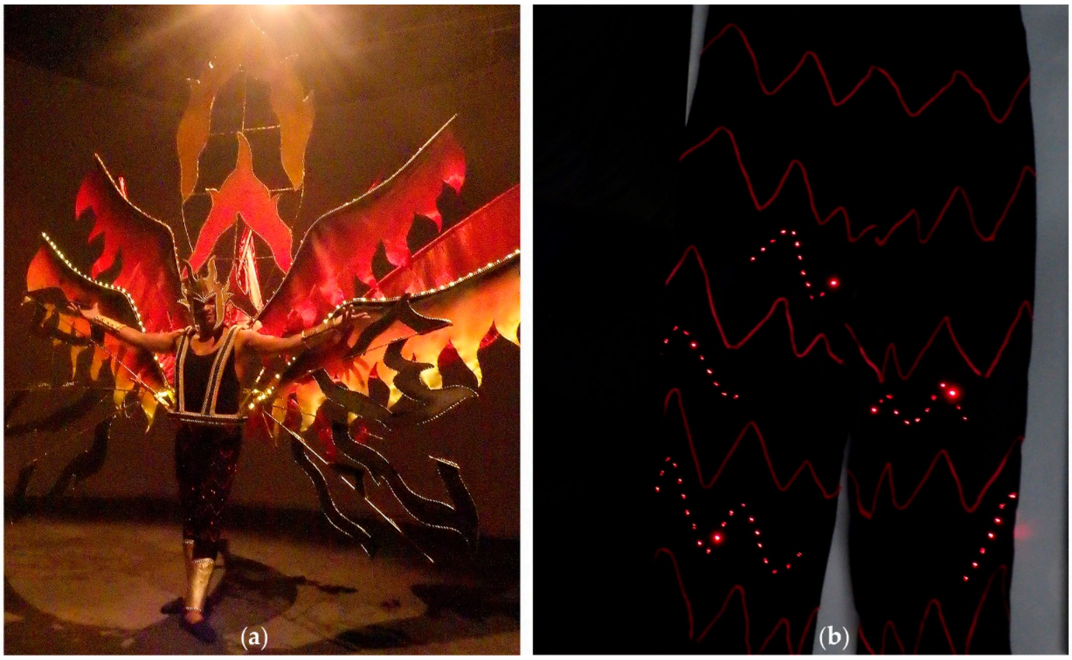

Figure 6. The completed costume. (**a**) The full costume incorporating the unitard, worn by Gil Santos. (**b**) A detail of the LED-yarns on the unitard legs, shown on a mannequin.

3.1. E-Yarn Connection Breakages

Tensile testing was performed to assess whether use of a curved E-yarn pattern of attachment to stretch fabric prevented breakage within the E-yarns. Examples of the tested samples are shown in Figure 7, and the results of tensile testing are provided in Figure 8. Each sample was tested over six cycles of increasing and decreasing strain. Breakages occurred during the first cycle of testing, so results from the first cycles of each test are displayed in Figure 8. The graph and continuity tests showed breakages in all of the samples containing a straight length of E-yarn. The samples containing a single length of curved E-yarn all remained intact, demonstrating that the curved placement of E-yarn on stretch fabric was effective at preventing E-yarn breakage. Ruptures occurred in all of the samples that incorporated a connection between two pieces of E-yarn. These breakages occurred at between 39% and 49% strain, as shown by the notches in the curves in Figure 8. The maximum stretchability of the fabric with attached, connected LED-yarns was therefore considered to be just below the lower measured strain value of 39%. This strain was considered to be well over the limit of strain to which the 10% Lycra® fabric would be subjected during performance. We therefore considered that the chosen methods of E-yarn placement, embroidery, and E-yarn connection were sufficient to ensure that the E-yarn circuitry remained intact.

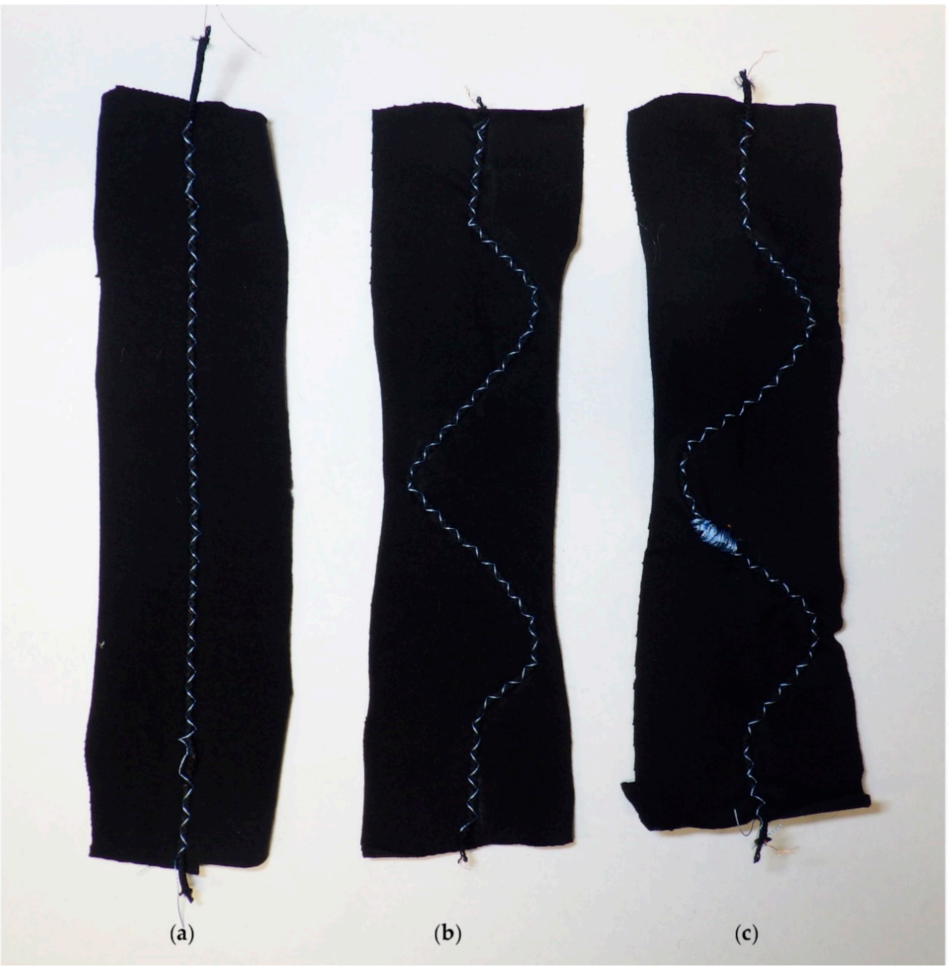

Figure 7. Samples of stretch fabric with attached E-yarns as prepared for tensile testing. From left: (**a**) Straight E-yarn; (**b**) Curved E-yarn; (**c**) Two curved E-yarns with a connection covered by a satin stitch.

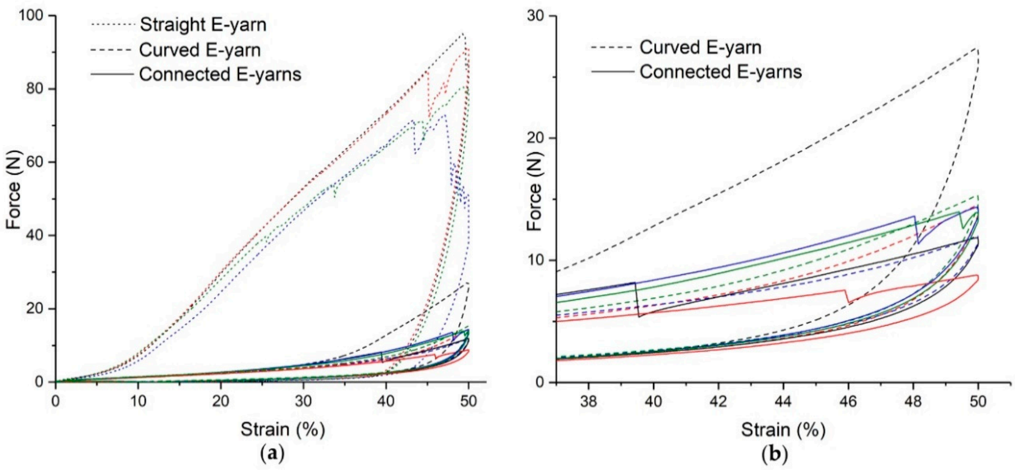

Figure 8. Results from the first cycles of cyclic tensile testing of the E-yarns attached to stretch fabric: (**a**) Notches near the top of the dotted curves show failure of straight E-yarns attached to stretch fabric; (**b**) The dashed lines in this detail from (**a**) show how E-yarns attached to the samples in a curved pattern remained intact. Notches in the solid lines show breakages in connections between curved E-yarns.

During performance, the E-yarns themselves remained intact, but many connections between E-yarns broke, causing the loss of illumination from some lines of LEDs that was apparent during the dance performance. We believed that these breakages happened when the unitard was pulled on by the performer, as the unitard underwent the greatest level of stretching during this process. The breakages occurred despite the assessment after tensile testing that connections between E-yarns would remain intact until beyond the level of strain at which the fabric would be permanently damaged. These breakages of connections also occurred despite the earlier work to reinforce the junctions between E-yarns after breakages occurred during attachment of E-yarns to the unitard.

The connections between the E-yarns were uncovered to check where the breakages had occurred and the weakest links were found to be the solder joints between wires. These areas were not completely covered with resin. This discovery was further confirmed after inspecting the broken links using a microscope (Keyence VHX-5000 Digital Microscope, Keyence (UK) Ltd., Milton Keynes, UK) as shown in Figure 9a. To correct this, the connections were re-soldered and then covered with a higher-viscosity resin (Dymax 9001-E-V3.7, Dymax Corporation, Torrington, CT, USA), ensuring that each solder joint was completely covered with resin.

Small areas of fabric were possibly subjected to high levels of strain at points where the E-yarn connections were embroidered into place. To prevent excess tension at the connecting points between E-yarns, we determined that longer lengths of E-yarn should be used to form zig-zags between connections. Extra lengths of black E-yarn were added in zig-zag patterns adjacent to connection points, as shown in Figure 9b.

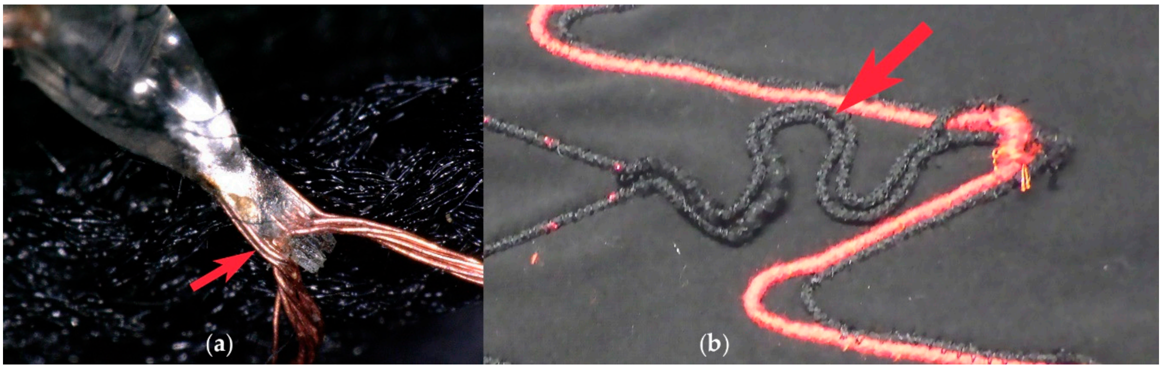

Figure 9. Breakage analysis of the E-yarns. (**a**) Connection between two copper wires magnified 100 times. The arrow indicates an area that is not covered by resin. (**b**) The arrow indicates a zig-zag connection between black LED-yarn and red E-yarn. This was added to reduce further breakages.

3.2. *Washability*

This prototype costume was not designed to be washed, but E-yarns in general are designed to be washable. Since creating the costume, initial wash tests have been completed. Five LED-yarns attached to clothing were machine washed and tumble dried. The LED-yarns still functioned after 7–25 washes, after which the test was stopped. Less aggressive methods of washing and drying, such as hand washing and line drying, are expected to lead to even greater longevity of LED-yarns. Future costumes containing E-yarns worn next to the skin can therefore be designed to be washable.

4. Discussion

This project demonstrated the flexibility of E-yarns, including the ability to attach E-yarns to skin-tight clothing without impeding the movement of a dance performer. The main hurdle for the use of numerous E-yarns on stretch fabric was found to be the creation of strong connections between the E-yarns. The method of forming the connections was improved during the fabrication of the costume, and afterward, but the process was time consuming. Each connection required soldering, application of resin, and couching in place while ensuring sufficient slack was left in the E-yarn on either side of the connection point. This was still not always sufficient to ensure that the connections remained unbroken during use. Ideally, the E-yarns themselves would be extendable, so that straight E-yarns could be attached to stretch fabric, without the need to zig-zag the E-yarn across the fabric surface. Further work is required to find a method of easily joining E-yarns easily to create robust junctions between flexible E-yarns, which can be relied upon to remain intact during use. This development will help ensure the feasibility and more widespread use of E-yarns.

LED Illumination

The illumination from the LEDs within the E-yarns was low, especially in contrast with the other LED lighting systems used on the upper parts of the costume, causing difficulties for audience members to see the LED-yarns that were key to the costume design. Ideally, the design would have been revised before the final assembly of the costume with white or lighter colored LEDs and a lighter or transparent textile on the outside of the E-yarns, resulting in more brightly-illuminated E-yarns. The preparation of the costume for a specific competition within the project timeframe did not allow for this modification. LEDs are best at visually demonstrating that E-yarns contain electronics, so a design containing brighter LEDs could be useful in demonstrating the existence of E-yarns.

The potential for much greater use of E-yarns lies in the range of electronic dyes and circuitry that can be incorporated within the E-yarns. LEDs provide a visible method of demonstrating this capability, so LED-yarns are important for their ability to catch the eye, drawing viewers in for further discussion about the technology.

5. Conclusions

The design of a carnival costume and its use in performance showed that electronic yarns (E-yarns) could be attached to stretch fabric for use in dance without impeding the movements of the dancer. This was the primary aim of our project. The LEDs within the LED-yarns functioned on the costume, although some electrical connections broke, resulting in a lack of illumination from some parts of the circuit. The low visibility of the red LEDs within the LED-yarns, plus the loss of some connections between the E-yarns, meant that a secondary design aim of demonstrating the existence of E-yarns to a wide audience was not completely fulfilled. Further work is required to create robust connections between E-yarns to ensure that the stretching of underlying fabric does not result in ruptured connections. Brighter LEDs within light-colored or clear LED-yarn would be more appropriate for use in a costume where higher visibility of the LEDs is required.

The design, fabrication, and testing in performance of this costume illustrate the potential for incorporating lighting into applications where flexibility is required, with the lighting as an integral part of a textile that does not impede the movement of the wearer. E-yarns can be designed to include many types of sensor, as well as LEDs, so the potential for integration of sensors into many types of stretchable clothing is illustrated.

Author Contributions: D.A.H., A.S. and T.H.-R. designed the study. D.A.H., V.S. and A.S. conducted the experiments. D.A.H. performed the data analysis. L.C. and V.S. designed the costume. A.M., V.S., L.C. and T.H.-R. fabricated the costume. A.M. provided specialist technical expertise. D.A.H. wrote the paper. All authors discussed the results and contributed to producing the final manuscript.

Funding: This research was funded by the Engineering and Physical Sciences Research Council under grant number EP/M015149/1 as a partnership project entitled "Use of electronic yarn in stretch fabric for the performing arts".

Acknowledgments: The authors would like to thank Steven Hoyte of Mas Rampage for construction of the costume frame; Carlos Oliveira, Ioannis Anastasopoulos, Mohamad Nour Nashed, and Achala Satharasinghe (of the Advanced Textiles Research Group, Nottingham Trent University), for technical assistance, especially in the fabrication and connection of E-yarns; Alice Cobbin and Evie Cobbin for assistance with the fabrication of the costume; and Tom Fisher and Kath Townsend of Nottingham Trent University for advice on the writing of this paper. The authors would also like to thank Gil Santos for dancing in the costume. Finally, the authors would like to express gratitude to Tatiana Woolley of ABC Dance School, Nottingham, for collaboration on the costume design, fabrication assistance, and organisation of dance performances.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Hayward, J. E-Textiles 2017–2027: Technologies, Markets, Players. Available online: https://www.idtechex.com/research/reports/e-textiles-2017-2027-technologies-markets-players-000522.asp (accessed on 8 February 2018).
2. Dias, T.K. Electronically Functional Yarns. World Patent WO2016/038342 A1, 17 March 2016.
3. Dias, T.; Hughes-Riley, T. Electronically Functional Yarns Transform Wearable Device Industry. *R D Mag.* **2017**, *59*, 19–21.
4. Hardy, D.A.; Anastasopoulos, I.; Nashed, M.N.; Oliveira, C.; Hughes-Riley, T.; Komolafe, A.; Tudor, J.; Torah, R.; Beeby, S.; Dias, T. An Automated Process for Inclusion of Package Dies and Circuitry within a Textile Yarn. In Proceedings of the Design, Test, Integration & Packaging of MEMS/MOEMS, Rome, Italy, 22–25 May 2018.
5. Rathnayake, A.S. Development of the Core Technology for the Creation of Electronically-Active, Smart Yarn. Ph.D. Thesis, Nottingham Trent University, Nottingham, UK, 2015.
6. Hughes-Riley, T.; Lugoda, P.; Dias, T.; Trabi, C.; Morris, R. A Study of Thermistor Performance within a Textile Structure. *Sensors* **2017**, *17*, 1804. [CrossRef] [PubMed]
7. *EMCCAN "Carnival Clash" King and Queen Show*; Theatre Performance at Nottingham Playhouse: Nottingham, UK, 2017.
8. Cork, C.; Dias, T.; Acti, T.; Ratnayaka, A.; Mbise, E.; Anastasopoulos, I.; Piper, A. The next generation of electronic textiles. In Proceedings of the 1st International Conference on Digital Technologies for the Textile Industries, Manchester, UK, 5–6 September 2013.
9. Guler, S.D.; Gannon, M.; Sicchio, K. *Crafting Wearables: Blending Technology with Fashion*; Apress: Berkeley, CA, USA, 2016; ISBN 1484218086.
10. Anonymous. The Electric Diadems of the New Ballet "La Farandole". *Sci. Am.* **1884**, *50*, 163.
11. Cook, J. How to Light Up Your Clothing. Available online: http://www.wired.co.uk/article/light-up-your-clothing (accessed on 1 November 2017).
12. Scottish Opera. The Magic Flute: Production Details. Available online: https://www.scottishopera.org.uk/for-hire/productions-for-hire/productions/the-magic-flute/ (accessed on 1 November 2017).
13. Anon Tron Dance—All about LED Dance Performance! Available online: http://www.trondance.com (accessed on 31 October 2017).
14. EL Wire Craft EL Wire and EL Tape. Available online: http://elwirecraft.co.uk/ (accessed on 1 November 2017).
15. Waldemeyer, M. Olympic Ceremonies—Moritz Waldemeyer. Available online: http://www.waldemeyer.com/olympic-ceremonies (accessed on 2 August 2017).
16. Moritz Waldemeyer Bono's Laser Jacket for the U2 360 Tour. Available online: http://www.waldemeyer.com/bonos-laser-jacket-u2-360-tour (accessed on 1 November 2017).
17. Pantouvaki, S. Embodied interactions: Towards an exploration of the expressive and narrative potential of performance costume through wearable technologies. *Scene* **2014**, *2*, 179–196. [CrossRef]
18. Anonymous. EFM: Apparel, Accessories, Advertisement. Available online: http://www.electroflashmedia.com/ (accessed on 1 November 2017).
19. CuteCircuit K-Dress—CUTECIRCUIT. Available online: http://shop.cutecircuit.com/products/k-dress-1?variant=267846634 (accessed on 12 December 2016).
20. Anonymous. About CuteCircuit. Available online: http://cutecircuit.com/about-cutecircuit/ (accessed on 1 November 2017).

21. *ASTM E8/E8M—16A Standard Test Methods for Tension Testing of Metallic Materials*; ASTM: West Conshohocken, PA, USA, 2016.
22. Achong, D. Mac Farlane Rules in Kings, Queens Prelims. Available online: http://www.guardian.co.tt/carnival/2012-02-11/mac-farlane-rules-kings-queens-prelims (accessed on 8 August 2017).
23. Mas Rampage Rampage Mas Band—Artists. Available online: http://rampagemasband.com/artists.html (accessed on 8 August 2017).