Knittable Sheath-Free E-Yarns Achieved Through Yarn Covering Technique

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I. INTRODUCTION

Recent advancements in electronic textiles have enabled the integration of sensing, illumination, and communication functions directly into fabrics, opening new possibilities in healthcare, sports, and wearables. A key innovation in electronic textiles is the development of electronic yarns, which embed miniature electronic components, such as LEDs, within textile-compatible yarns. Traditional E-yarn fabrication includes a sheathing step using knit braiding to protect electronic components and interconnects; however, this process significantly increases yarn diameter, introduces stiffness and requires specialized machinery, thus limiting compatibility with fine textile structures. This study proposes a simplified fabrication approach that eliminates the conventional sheathing stage by using an alternative yarn covering technique that still provides necessary mechanical and environmental protection to the embedded LEDs before knitting. Even without the sheathing process, the developed E-yarns remain compatibility with standard knitting processes, as experimentally demonstrated using a computerized flatbed knitting machine with standard yarn feeders and tensioning devices. Experimental validation further demonstrated significant reductions in yarn diameter (down to ~1.3mm from ~1.5–2mm in prior work), improved flexibility, and simplified manufacturing without compromising mechanical durability or LED functionality. The proposed technique offers a viable pathway for scalable, comfortable, and mechanically robust integration of smart functionality seamlessly into textile systems.

II. LITERATURE REVIEW

The integration of electronics into textiles has led to the development of smart textiles, which can be adapting functionality based on environmental stimuli [1][2][4]. These innovative fabrics are used in healthcare monitoring, environmental sensing, and entertainment by embedding sensing and active components within fabric [1][2][3][4]. Smart textiles are classified into three generations based on electronic integration [1]. First-generation systems use surface-mounted rigid components, but lack flexibility and washability [1][5]. Second-generation designs embed conductive fibres through knitting or weaving, offering better comfort but limited functionality [1]. Third-generation E-yarns integrate electronics within yarns, retaining textile properties while enabling advanced functions with improved durability and scalability [1][3][5][6]. E-yarn technology supports the integration of various electronic components such as sensors, MEMS, LEDs, and RFID tags enabling functions like illumination, temperature monitoring, and vibration sensing [1][2][5]. The common E-yarn fabrication process involves four stages: soldering electronic components onto fine copper wires [1][2][3][5], encapsulating them in resin micro-pods for protection [1][2][5], optionally covering with textile yarns to retain yarn-like properties [1][7] and finally applying a warp-knitted sheath (knit braiding process) using a circular machine to enhance softness, stretch and mechanical durability [1][2][7]. However, this sheathing step has limitations such as it requires specialized Raschel machines with core yarn insertion and increases yarn diameter by ~80% making the yarn bulkier and potentially less flexible for fine textile structures [5][7]. This study eliminates the need for the complex knit-braiding step by finalizing E-yarn fabrication after the covering stage [7].

III. MATERIALS AND METHODS

A. *Fabrication of the Core of the E-yarns*

Pre-soldered 0402 SMD (Surface-Mount Device) blue LEDs (WJDG-Model, HUAN Store, China; 1.0 × 0.5 × 0.5 mm) were interconnected in series [Fig. 1] using 38 AWG silver-plated copper wires coated with PTFE (Qian Fang Store, China)[4]. The tensile strength test (ISO 2062:2009) was conducted on the individual wires, wire-to-wire and wire-to-chip joints. These tests were done to identify the critical failure points, highlighting the need for targeted reinforcement during encapsulation. Three carrier yarn types: 20S poly/cotton (60/40), 150D/144F polyester draw-textured yarn (DTY) and 50D/72F ultra-high molecular weight polyethylene (UHMWPE) were evaluated to select the one with higher tensile strength. The assembly circuit was wrapped around the carrier yarn [Fig. 2] encapsulated the package dies within a 1 mm × 4 mm silicone mould using UV-curable epoxy resin (1300–1600 cps) [1] and cured under 365 nm UV for one minute. Finally, tensile strength tests (ISO 2062:2009 standard) were conducted on all three sample types to assess their breaking strength.

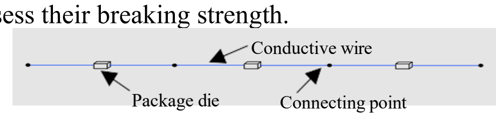

Fig. 1. Diagram illustrating the series connection of SMD LED package dies and conductive wires during core formation.

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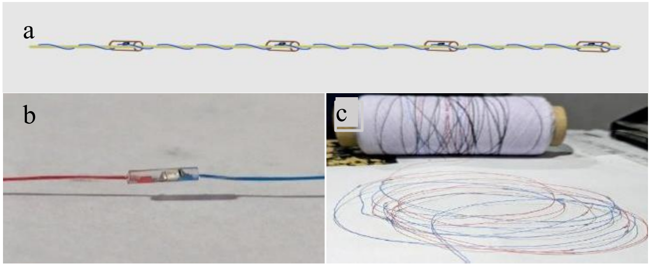

Fig. 2. (a) Diagram showing the final appearance of the encapsulated core yarn. (b) Close-up view of a resin macro-pod encapsulating an LED. (c) The finished core yarn with LEDs and connections fully encapsulated.

B. *Final Yarn Formation*

In the final fabrication stage a covering process (in lieu of knit-braiding) was performed to protect the encapsulated core and improve yarn cohesion. Using a Menegatto covering machine, Nylon 6,6 filament yarn was applied at varying yarn counts (22, 156, and 312 denier) and twist levels (600, 1200, and 1800 TPM) producing nine sample combinations (Table 1). Machine speed (6062 rpm) and core yarn stretch (×1) were kept constant. Ten repetitions per sample ensured reliability, and optimum parameters were identified based on tensile strength (ISO 2062:2009), light intensity and yarn diameter to balance durability and integration compatibility.

TABLE I. COVERING PARAMETER COMBINATIONS FOR E-YARN SAMPLES

Sample No.	Covering Yarn Count (D) (Nylon 6,6)	Twist Per Meter
1	22	600
2	22	1200
3	22	1800
4	156	600
5	156	1200
6	156	1800
7	312	600
8	312	1200
9	312	1800

C. *Yarn Diameter Testing of the E-Yarn*

E-yarn diameters were measured using a YIZHAN HDMI microscope with Vividia AbleScope software at 40× magnification. Five measurements were taken from each of ten images per sample (50 readings total), using the software's calibration scale and the mean value was calculated for the final diameter.

D. *Light Intensity Testing of the E-Yarn*

LED light intensity was measured to evaluate the effect of the covering process using a Yokogawa 51021 digital lux meter in a dark room. Each E-yarn sample was powered at 2.7 V and measured at a 15 cm distance with eight readings taken around the LED in the same horizontal plane. The average of these readings was recorded as the final light intensity value.

E. *Integration of E-Yarns into Knitted Textile Structure*

Knitting was performed on a 10-gauge Shima Seiki computerized flatbed machine with the E-yarn guided through standard tension devices and feeders. To avoid damage from 180° bending during loop formation the E-yarn was used solely as an inlay within a modified weft-knit spacer structure [Fig. 3]. This configuration positioned the E-yarn between independent face and back knit loops, secured by tuck stitches for stability and protection. A 6-ply Nylon 6,6 ground yarn (111 denier, 36 filaments) and a double-covered spandex connecting yarn (44 denier spandex core with 56 denier Nylon 6,6 cover) were used, maintaining material consistency with the E-yarn covering.

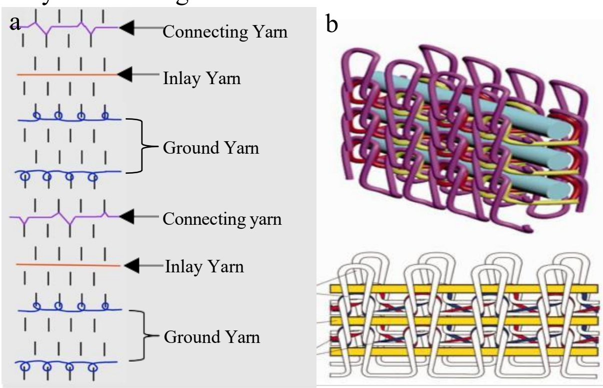

Fig. 3. Knitting structure for inlay integration. (a) Yarn path diagram of the weft-knit spacer fabric, showing separate ground layers and an inlaid E-yarn.. (b) 3D schematic of the resulting fabric structure with the E-yarn

IV. RESULTS AND DISCUSSION

A. *Weakest Links within the Circuit Assembly*

Tensile test results (Table 2) showed the highest strength for individual wires (3.728 N), followed by wire-to-wire connections (2.912 N) and wire-to-SMD chip joints (2.747 N) (Fig. 4). The reduced strength at soldered connections is attributed to the limited contact area of the SMD chip pads (400 µm × 500 µm). To address this epoxy encapsulation was applied to both wire-to-chip and wire-to-wire junctions providing mechanical reinforcement against stress and environmental damage.

TABLE II. BREAKING STRENGTH OF CORE COMPONENTS (INDIVIDUAL WIRE VS. SOLDERED CONNECTIONS)

Specimen	Breaking Strength (N)
Individual Wires	3.728
Wire to Wire Connection points	2.912
Wire to SMD connections points	2.747

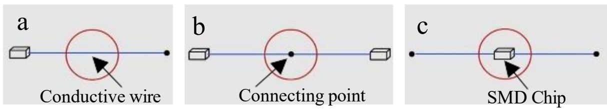

Fig. 4. Illustrates the three types of specimens prepared for the tensile tests: (a) individual wire, (b) wire-to-wire junction and (c) wire-to-chip junction

B. *Selection of the Carrier Yarn*

Tensile testing of encapsulated cores (Table 3) showed that carrier yarn selection must consider factors beyond breaking strength including modulus and wicking properties. Polyester filament yarn cores (12.682 N) break mainly at the conductive wire due to stretch-induced tension transfer and exhibited reduced flexibility due to resin spread. Poly-cotton staple yarn cores (10.756 N) failed in the yarn itself, with even tension distribution and reduced resin spread than polyester yarn. UHMWPE yarn cores achieved the highest strength (19.816 N), with minimal stretch, no resin spread and no damage to conductive wires leading to its selection as the carrier yarn for this study.

TABLE III. BREAKING STRENGTH OF ENCAPSULATED CORE USING DIFFERENT CARRIER YARNS

Specimen	Breaking Strength (N)
20S poly/cotton 60/40 staple yarn	10.7569
150D/144F polyester draw textured yarn	12.6822
50D/72F ultra high molecular weight polyethylene (UHMWPE) yarn	19.8156

C. Influence of Covering Parameters on Yarn Strength, Diameter and Light Intensity

1) Breaking Strength

Tensile testing after the covering process (Table 4) showed that increasing covering yarn count significantly improved breaking strength at all TPM levels, with 312D yarns exhibiting the highest strength (23.92 N) due to greater structural support. Higher TPM (21.106 N at 1800 TPM) values also enhanced tensile strength across all yarn counts by improving fibre cohesion and stress distribution, thereby reducing weak points and increasing load-bearing capacity.

2) Yarn Diameter

Yarn diameter testing after the covering process (Table 4) revealed that covering yarn count strongly affects final diameter, with higher denier yarns producing bulkier structures due to increased fibre volume. The largest diameter (1.4301 mm) was observed in the 312D/600 TPM sample, while TPM showed no significant influence, as diameter variations were mainly determined by yarn count.

3) Light Intensity

Light intensity tests (Table 4) showed that increasing covering yarn count reduces LED brightness, with the highest intensity at 22D/600 TPM (19.47 lux) and the lowest at 312D/1800 TPM (17.02 lux), due to denser yarns obstructing light. Similarly, higher TPM values decreased brightness across all yarn counts by increasing fibre density and compactness, limiting light transmission.

TABLE IV. EFFECTS OF COVERING YARN COUNT (DENIER) AND TPM ON THE FINAL E-YARN PROPERTIES: BREAKING STRENGTH (N), DIAMETER (MM) AND LED LIGHT INTENSITY (LUX)

No.	Covering Yarn Count (D)	TPM	Breaking Strength	Yarn Diameter	Light Intensity
1	22	600	20.172	1.206	19.475
2	22	1200	20.75	1.183	18.875
3	22	1800	21.106	1.148	18.25
4	156	600	22.964	1.428	18.4
5	156	1200	23.502	1.339	18.05
6	156	1800	24.175	1.304	18
7	312	600	23.918	1.430	17.425
8	312	1200	25.082	1.422	17.4
9	312	1800	25.98	1.424	17.025

D. Selection of the Optimal Covering Yarn Parameters

Covering density analysis (Fig. 5) identified samples 5–9 as providing substantial wire coverage with samples 6, 8 and 9 offering superior encapsulation of LEDs. Sample 6 featuring a breaking strength of 24.175 N, diameter of 1.304 mm and light intensity of 18.0 lux balanced protection and performance optimally. This diameter is smaller than typical E-yarns reported in literature (1.5–2 mm) [5][7] and its strength far exceeds knitting tensions.

E. Knittability of the E yarn

Despite increased diameter and stiffness the developed E-yarn passed smoothly through flatbed knitting machine standard yarn path without any damage. It was successfully integrated as an inlay within a modified weft-knit spacer fabric withmachine issues observed, demonstrating its compatibility with conventional knitting processes (Fig. 5).

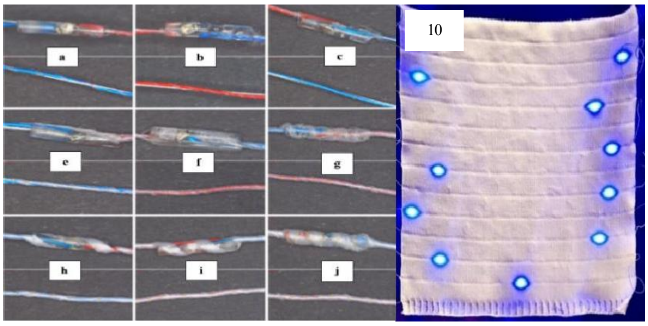

Fig. 5. Appearance after covering E-yarns. The top view of the encapsulated LED area, while the bottom side shows the conductive wire area for each of the following samples: (1) Sample 1, (2) Sample 2, (3) Sample 3, (4) Sample 4, (5) Sample 5, (6) Sample 6, (7) Sample 7, (8) Sample 8, (9) Sample 9, (10) Illuminated knitted fabric after supplying power, highlighting a successful integration of LED yarns.

V. CONCLUSION

This study developed an improved E-yarn fabrication process using a yarn covering method and weft-knitted fabric structure, overcoming drawbacks of traditional sheathing. UHMWPE was selected as the optimal core yarn based on superior tensile strength. Nine samples with varying cover yarn counts and TPM were evaluated for strength, diameter and light intensity. Sample 6 (156D, 1800 TPM) demonstrated the best balance of strength (24.2 N), diameter (~1.3 mm) and light intensity (18 lux) producing a finer yet durable yarn suitable for knitting (~1.5–2 mm in traditional method). The finalized E-yarn was successfully integrated into weft-knitted fabric using industrial knitting techniques without breakages. While this study demonstrated LED integration, the same yarn architecture can embed sensors, MEMS or RFID tags for applications like temperature or vibration monitoring. Future work may explore different devices and wash durability to validate long-term use highlighting the potential of fully integrable E-yarns in smart textiles.

REFERENCES

[1] M.-N. Nashed, D. A. Hardy, T. Hughes-Riley, and T. Dias, 'A Novel Method for Embedding Semiconductor Dies within Textile Yarn to Create Electronic Textiles', *Fibers*, vol. 7, no. 2, p. 12, Jan. 2019, doi: 10.3390/fib7020012.

[2] A. Satharasinghe, T. Hughes-Riley, and T. Dias, 'Photodiode and LED Embedded Textiles for Wearable Healthcare Applications', in *Autex*, openjournals ugent, Aug. 2019. doi: 10.21825/autex.63843.

[3] D. Hardy, A. Moneta, V. Sakalyte, L. Connolly, A. Shahidi, and T. Hughes-Riley, 'Engineering a Costume for Performance Using Illuminated LED-Yarns', *Fibers*, vol. 6, no. 2, p. 35, Jun. 2018, doi: 10.3390/fib6020035.

[4] A. Rathnayake and T. Dias, 'Yarns with embedded electronics', in *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers. (UbiComp '15)*, Osaka, Japan: ACM Press, 2015, pp. 385–388. doi: 10.1145/2800835.2800919.

[5] D. A. Hardy et al., 'Wash Testing of Electronic Yarn,' *Materials*, vol. 13, no. 5, p. 1228, Mar. 2020, doi: 10.3390/ma13051228.

[6] T. Hughes-Riley, P. Jobling, T. Dias, and S. H. Faulkner, 'An investigation of temperature-sensing textiles for temperature monitoring during sub-maximal cycling trials,' *Textile Research Journal*, vol. 91, no. 5–6, pp. 624–645, Mar. 2021, doi: 10.1177/0040517520938144.

[7] D. Hardy, I. Anastasopoulos, M.-N. Nashed, C. Oliveira, T. Hughes-Riley, A. Komolafe, J. Tudor, R. Torah, S. Beeby, and T. Dias, 'An automated process for inclusion of package dies and circuitry within a textile yarn', in *2018 Symposium on Design, Test, Integration & Packaging of MEMS and MOEMS (DTIP), Roma*: IEEE, May 2018, pp. 1–5. doi: 10.1109/DTIP.2018.8394189.