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Conductive Yarn Embroidered Circuits for System on Textiles

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Abstract

With the recent convergence of electronics and textile technology, various kinds of smart wearables are being developed, such as heating clothes, health monitoring clothes, and motion sensing clothes. In this study, the novel conductive embroidery yarns for touch sensing and signal transmission for system on textile (SoT) are introduced. The conductive yarn for touch sensing can be used as a user interface of smart clothes by constructing an embroidery circuit. The conductive yarn for signal transmission can be embroidered on smart clothing and used as a transmission line to transmit power and signal. The conductive yarns and their embroidered circuits were characterized and SoT prototypes using the embroidered circuit of these conductive yarns were presented. These e-textiles based on touch sensing and signal transmission can be comfortably applied for SoT and maintain electrical performance without being damaged by tensile force generated by the movement of the wearer.

Keywords: smart wearables, system on textiles, e-textile, conductive yarns, embroidered circuits

1. Introduction

Wearing smart performance must be done very naturally and smoothly in order to be accepted by the public. Because textiles are breathable, lightweight, flexible, and robust, smart textiles are the most comfort wearables that can provide users with an intelligent environment by sensing, data processing and communication, and actuating. Thus, many studies on textile-based wearables have been conducted recently, and these studies cover topics such as textile-based full-body implementations, multifunctionality, customizability, and robust and seamless integration.

Jost et al. emphasized on devices made from textiles, suggesting the design concept of a smart power body suit where a piezoelectric patch of the knees, textile antennas between shoulder blades, and textile electrochemical energy storage at the waist back are integrated as part of a fabric with conductive yarns that act as leads to transmit energy or information throughout the garment. Body-worn sensors are unobtrusively embedded into a garment and distributed all over the body [1]. Lorussi et al. reported piezoresistive material-loaded, sensorized garments, such as gloves, leotards, and seat covers capable of reconstructing and monitoring body shape and postures [2].

PowerMatrix of Sefar AG is one of the leading multi-functional smart textiles. It is a hybrid fabric consisting of polyester monofilaments and metal monofilaments in warp and weft, which is possible to utilize for various purposes such as custom-made LED panels, temperature sensors, and heating fabrics [3, 4]. The e-fibers that combine various functionalities into the yarn structure simplify the fabrication process and interconnection-related issues and improve wearability [5, 6].

Customizability is another important issue in the field of e-textiles. The peregrine USB glove can be customized for over 30 user-programmable actions and allows the wearer to carry out those time-sensitive gaming commands with a switch of a finger by utilizing the touch sensitive pads embedded in the fingers and palm of the glove [7]. Buechley introduced a do-it-yourself (DIY) wearable electronics construction kit which includes a set of stitchable controllers, sensors, and actuators that enable novices to build their own system [8].

Issues with robust and seamless integration are critical to the feasibility of commercial manufacture and widespread consumer adoption. The EU-funded FP7 Place-it project focuses on the true integration of LED technology with flexible, stretchable, and textile substrates [9]. Likewise, the FP7 PASTA project focuses on electronic packaging and module interconnection to increase the robustness of integration by development of stretchable interposers to provide strain relief between components and fabrics [10].

In this context, embroidery techniques using conductive threads on substrate fabrics have become a very attractive approach for fabricating textile-based circuits for smart wearables because of their circuit design freedom and ease of manufacture compared to other processes such as weaving, knitting, and printing. Circuits can be easily patterned by employing a computer numerically controlled (CNC) embroidery using conductive threads. Embroidery also offers much more tailorability and customizability than other processes because they can be embedded in clothing at the end of the garment manufacturing process. Above all, it is a great advantage that the connection between the circuit embroideries and the small electronic components is possible to some extent during the embroidery process [11–14].

Two CNC embroidery methods, standard embroidery and tailed fiber placement (TFP), can be used to form the embroidered circuit [15]. In the standard embroidery method, the needle thread and the bottom thread form a double lock stitch forming a technically identical appearance on the upper side and the bottom side, respectively (**Figure 1a**). The CNC standard embroidery process allows for sophisticated work and enables the connection of flexible printed circuit board (FPCB) or small electronic elements and embroidered circuits during the embroidery process. And a one-stop production process for electronic textiles is also possible [16].

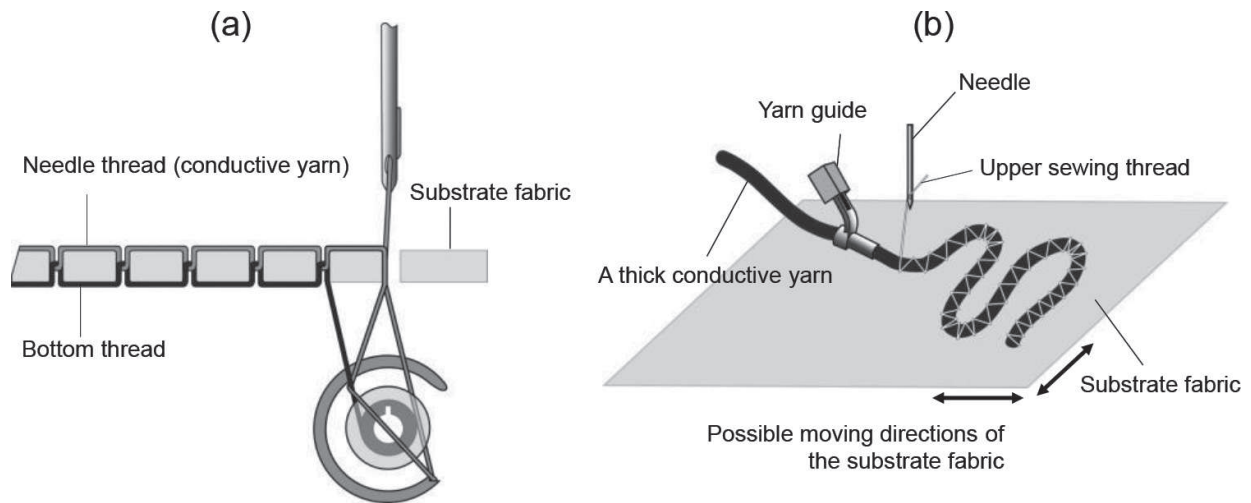


Figure 1. Embroidery methods: (a) standard embroidery forming double lock stitch and (b) the tailored fiber placement method.

On the other hand, the needle thread of the CNC standard embroidery machine is required to be thin and flexible and to have strength and yield strength to withstand stress during the embroidery process. On the other hand, TFP method is a three-thread system. The TFP method is used when the thread is very stiff, nonelastic and very thick like glass fiber or carbon fiber and cannot be worked on standard embroidery machine (**Figure 1b**). A thick conductive yarn is fixed on the substrate fabric with a set of top and bottom threads forming zigzag stitches. In the TFP method, the direct connection of the small electronic element and the embroidered circuit is impossible during the embroidery process.

Therefore, this section introduces metal composite embroidery yarns (MCEYs) that are very thin, flexible, very conductive, solderable and having suitable strength for the CNC standard embroidery process. In addition, several system on textiles (SoT) prototypes manufactured by the MCEY embroidery circuit method will be addressed.

2. Metal composite embroidery yarns

To make a very conductive, thin, flexible, robust, and solderable conductive embroidery yarn, we have developed metal composite embroidery yarns (MCEYs) consisting of superfine metal filaments and polyester filament yarns. During high-speed machine embroidery, the needle thread is subject to high stresses so that the needle thread requires high mechanical properties unlike the bottom yarn [17]. To ensure that the metal filaments contained in the MCEY are not stretched or broken during the embroidery process, the MCEY should have sufficient strength and yield strength as high as possible. In order to satisfy these conditions, two methods of type I and type II were developed (**Figure 2a**) [13, 18]. The metal filament is helically wrapped around the polyester yarn to minimize elongation against the longitudinal force. The type II method utilizes reinforcing polyester yarn in the plied yarn fabrication stage to increase the yield strength of MCEY over the type I method for external forces applied in the longitudinal

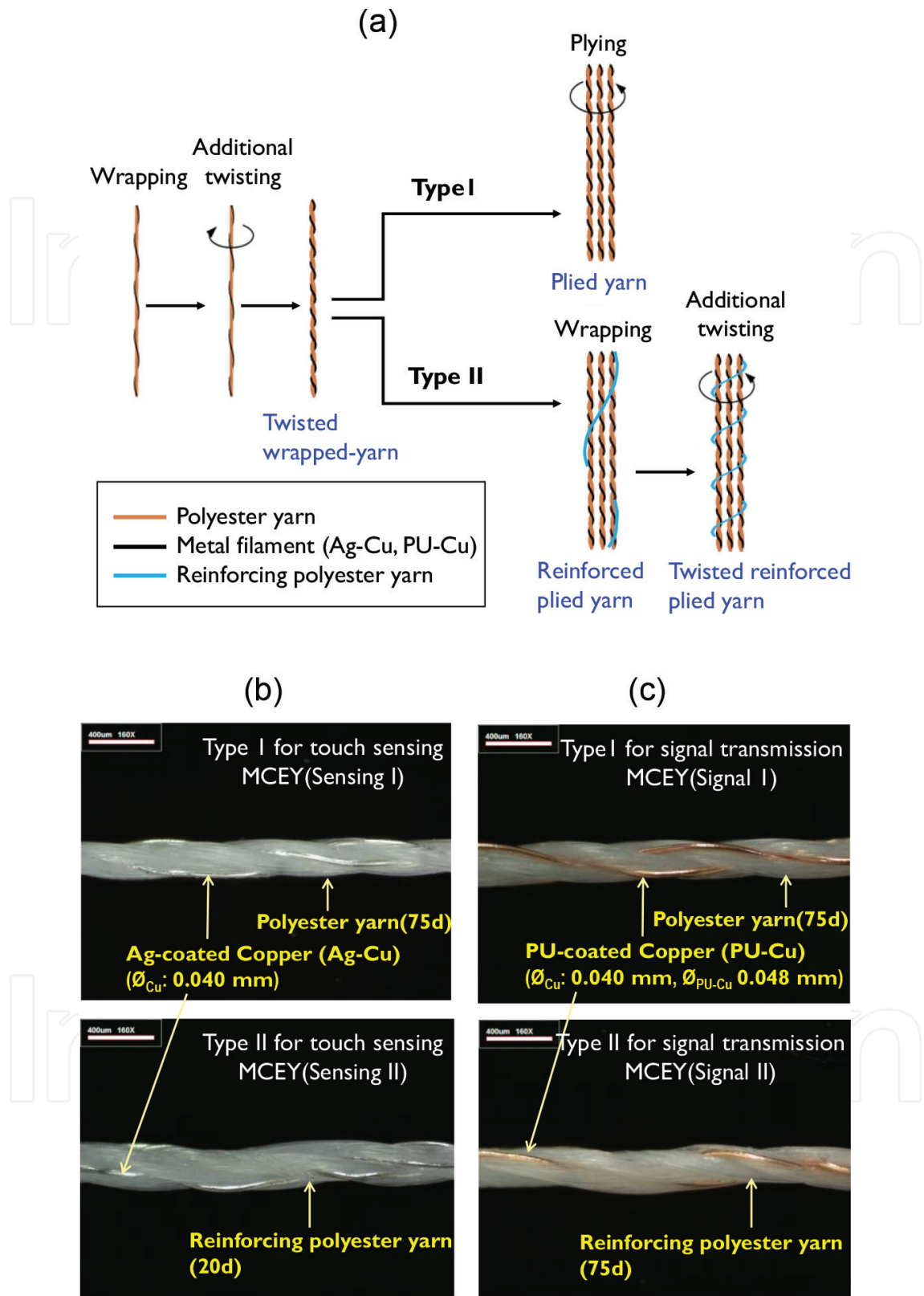


Figure 2. Structure of the MCEYs: (a) two types of metal composite yarn fabrication process [13], (b) side views of the MCEYs for touch sensing (type I and II) [18] and (c) side views of the MCEYs for signal transmission (type I and II) [13].

direction. On the other hand, two types of MCEYs were produced depending on the application. Ag-coated copper (Ag-Cu, \varnothing_{Cu} : 0.040 mm) and PU-coated copper (PU-Cu, \varnothing_{Cu} : 0.040 mm, \varnothing_{PU-Cu} 0.048 mm) were used as metal filaments for MCEY for touch sensing and MCEY for signal and power transmission respectively. In this way, the four MCEYs introduced in **Table 1** were developed with the optimum twist conditions obtained from the experiment.

2.1. Morphologies of MCEYs

Figure 2 illustrates the structures and side views of MCEYs. The smooth surface results in less friction on the yarn and the spiral structure of the metal filament reduces elongational deformation of the metal filament that can occur during the machine embroidery process.

Yarn type	Composition (wt% of Metal: Polyester)	Resistance (Ω /cm)	Linear density (denier)/ Yarn thickness (μm)	Load at yield (N)	Max. load (N)	Strain (%)
Sensing(I)	56.4: 43.6	0.0487	547/199	3.92	13.3	13.1
Sensing(II)	54.5: 45.5	0.0492	570/231	4.45	13.2	12.4
Signal(I)	57.3: 42.7	0.0521	549/200	3.92	13.3	13.1
Signal(II)	50.3: 49.7	0.0510	634/221	4.48	17.4	15.2

Table 1. Characteristics of the metal composite embroidery yarns (MCEYs).

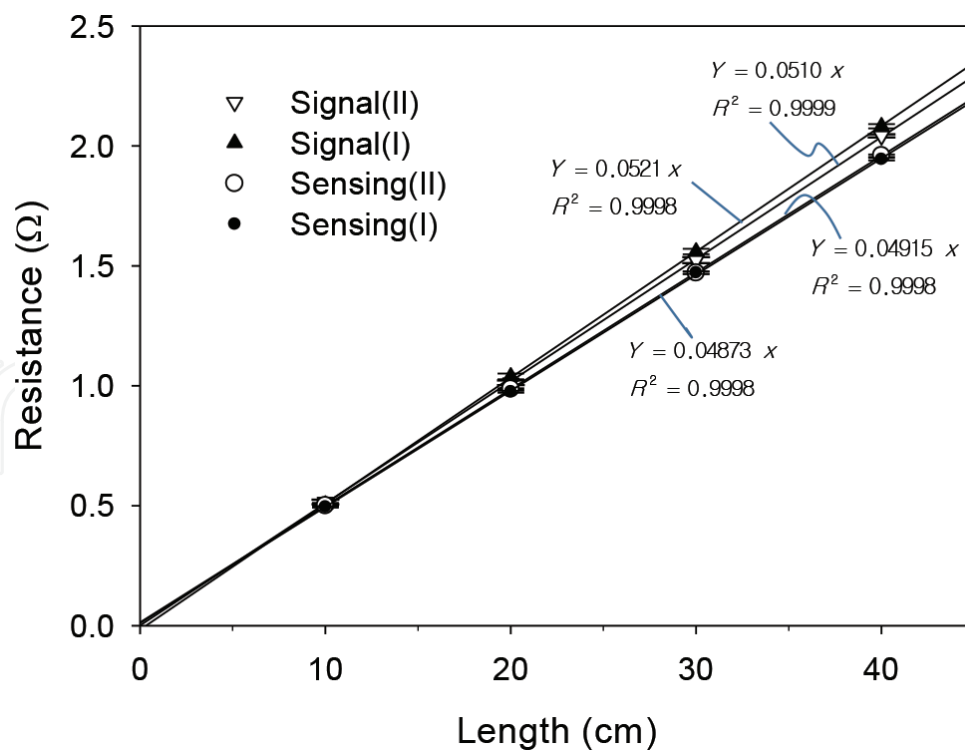


Figure 3. Electrical resistance linearity of four MCEYs as a function of the yarn length.

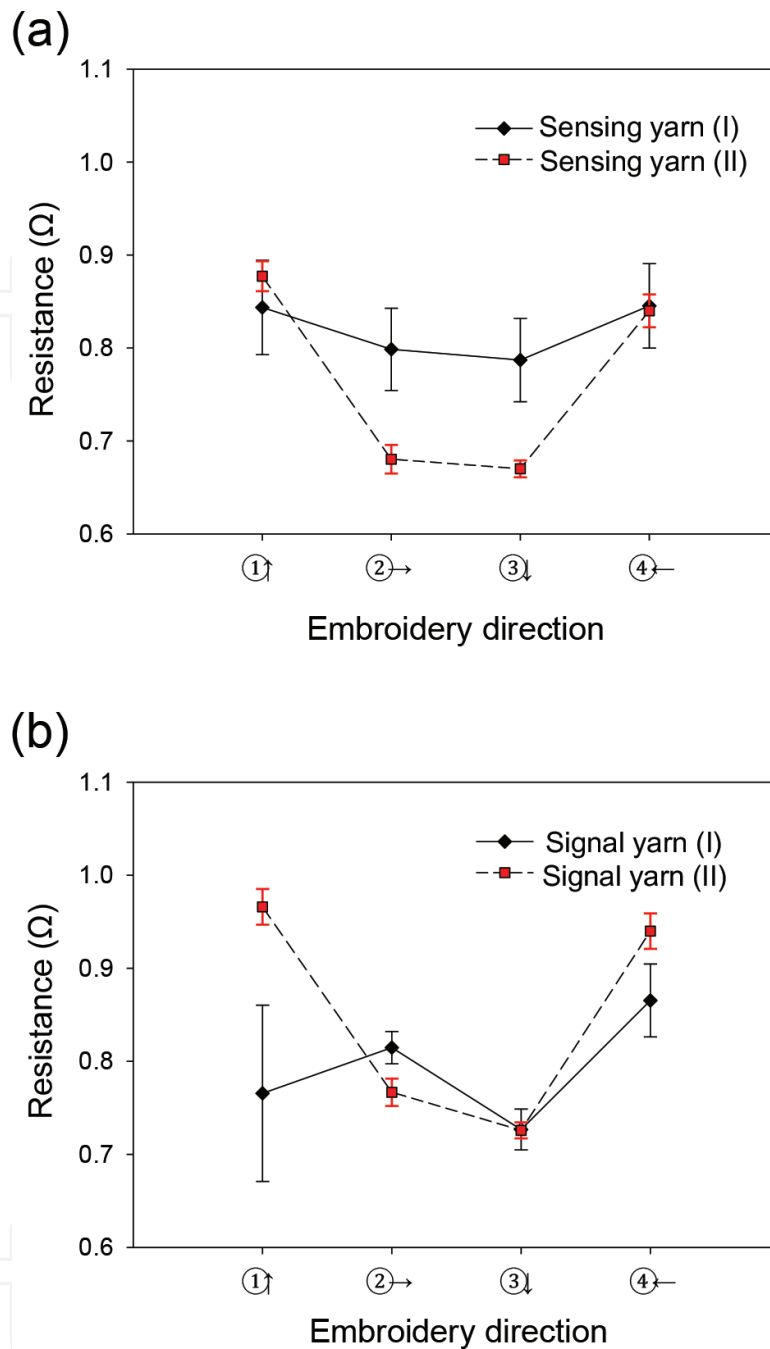


Figure 4. Electrical resistance of the MCEY embroidered circuit lines (10 cm circuit length, 2.5 mm running stitches): (a) touch sensing yarns (type I and II) embroidered circuits and (b) the signal yarns (type I and II) embroidered circuits.

Moreover, for type II structures, the reinforcing polyester yarn can increase the yield strength of MCEY and protect the metal filament of MCEY from friction during the embroidery process. Especially in the case of a sensing yarn, a metal filament spirals around the polyester yarn surface, so the twisted wrapped yarns made of metal filament and polyester yarn are electrically coupled in the final plied yarn, which provides a great advantage for touch sensing and electrical contact.

2.2. Tensile properties of MCEYs

As shown in **Table 1**, all MCEYs showed a very high tensile strength of 13 N or more. Especially for type II yarn, yield strength was increased by about 14% compared to type I yarn due to additional reinforcing polyester yarn.

2.3. Electrical properties of MCEYs

MCEYs were very thin and light but showed very low electrical resistance of about 0.05 Ω /cm (**Table 1**). The electrical resistances of MCEYs were measured 20 times for each length, and **Figure 3** shows the mean value, standard error, and linear regression equation for the electrical resistances of four MCEYs. As a result, electrical resistance increased very linearly as the length of yarn increased.

2.4. Electrical properties of MCEY embroideries

Figure 4 shows the effect of embroidery directions on the electrical resistance of the MCEY embroidery for both type I and type II. The values are the average of 20 samples. There were differences in resistance for each direction. D1 (front-to-back) and D4 (right-to-left) showed higher resistance than D2 (left-to-right) and D3 (back-to-front) in both type I and type II. Type II had a larger difference between resistance values in each direction than Type I. On the other hand, Type II had higher uniformity of electrical resistance than type I.

3. Sensing applications

3.1. Textile touch sensor manufactured by a one-stop production process

For wearables, textile interfaces are essential for the user to interact naturally with the smart function of the product [19, 20]. Electronic textiles, which measure the touched position or contact pressure, are the most widely used textile interface technologies [18, 21–24]. In most cases, a multilayer structured textile touch sensor that can sense the location of the user's touch can be used to manipulate the smart fashion system by mapping the command to the sensed location.

Figure 5 shows an example of a multilayer structured textile touch sensor that senses a touched position [16]. It shows a multilayer structure of a textile touch sensor composed of potentiometric resistive embroidery and an MCEY circuit pattern, a spacer fabric, and a conductive fabric for touch sensing. The spiral structure of the metal filament of MCEY provides the best conditions for electrical contact between the MCEY embroidered sensing pad and conductive fabric when pressed, and the MCEY satin stitch enables electrical connection with the resistive embroidery of the Ag-coated yarn. In addition, the standard CNC embroidery techniques enable a one-stop production of a multilayer structured textile touch sensor according to the four steps described in **Figure 5**. The conductive top layer and the MCEY circuit on the base layer can be electrically connected via a hole in the intermediate spacers and

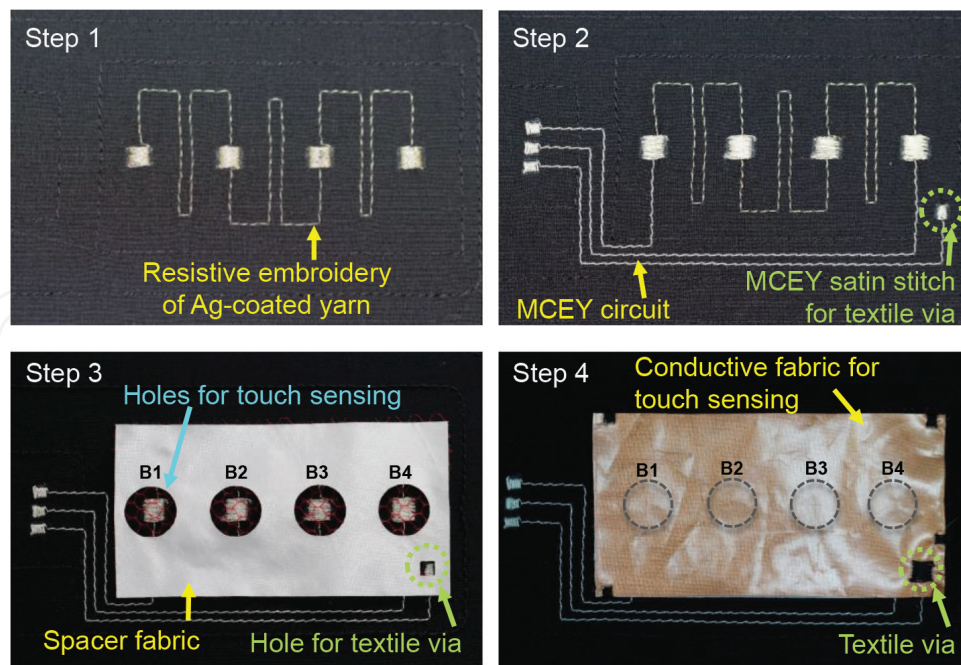


Figure 5. A one-stop production process on a standard CNC embroidery machine for fabricating the multilayer structured textile touch sensor that senses a touched position [16].

tightly fixed by a covering satin stitch of normal yarn. As a result, the connection portion with the external device can be formed in one layer. According to the contact resistance test for three textile via sizes (2×2 , 3×3 , and 4×4 mm), the overall contact resistance was lower than 0.15Ω . The smaller MCEY satin stitches of the textile exhibit lower contact resistance, which is more desirable for use. Similarly, by finger touch sensing test, the MCEY sensing pads of 3×3 mm– 5×5 mm showed a low contact resistance of less than 1Ω because they provide sufficient contact area during finger touch sensing.

In conclusion, the proposed one-stop production process allows a CNC embroidery machine to form precise circuit patterns while fabric layers are piled up one by one; the inner layer or interlayer circuits are electrically connected by embroidery, and individual fabric layers are also fixed to the base layer by embroidery. The multilayer fabric-structured electronic textiles constructed as such can contribute to securing the market competitiveness of smart textile systems.

3.2. Multitouch and pressure-sensing textiles

Figure 6 is another example of a multi-layer-structured textile touch sensor, which is a piezoresistive, multitouch sensing surface that senses pressure as well as touched position. Conductive-polymer-infused non-woven fabric by Eeonyx was used for piezoresistive substrate. The resistance of the piezoresistive fabric can be detected by sandwiching it between two conductors. To sense the position and pressure of the finger touch, the MCEY can be simply arranged in parallel on both sides of the piezoresistive fabric at right angles to each other. A 5 mm spacing was chosen to estimate the finger position with sufficient resolution

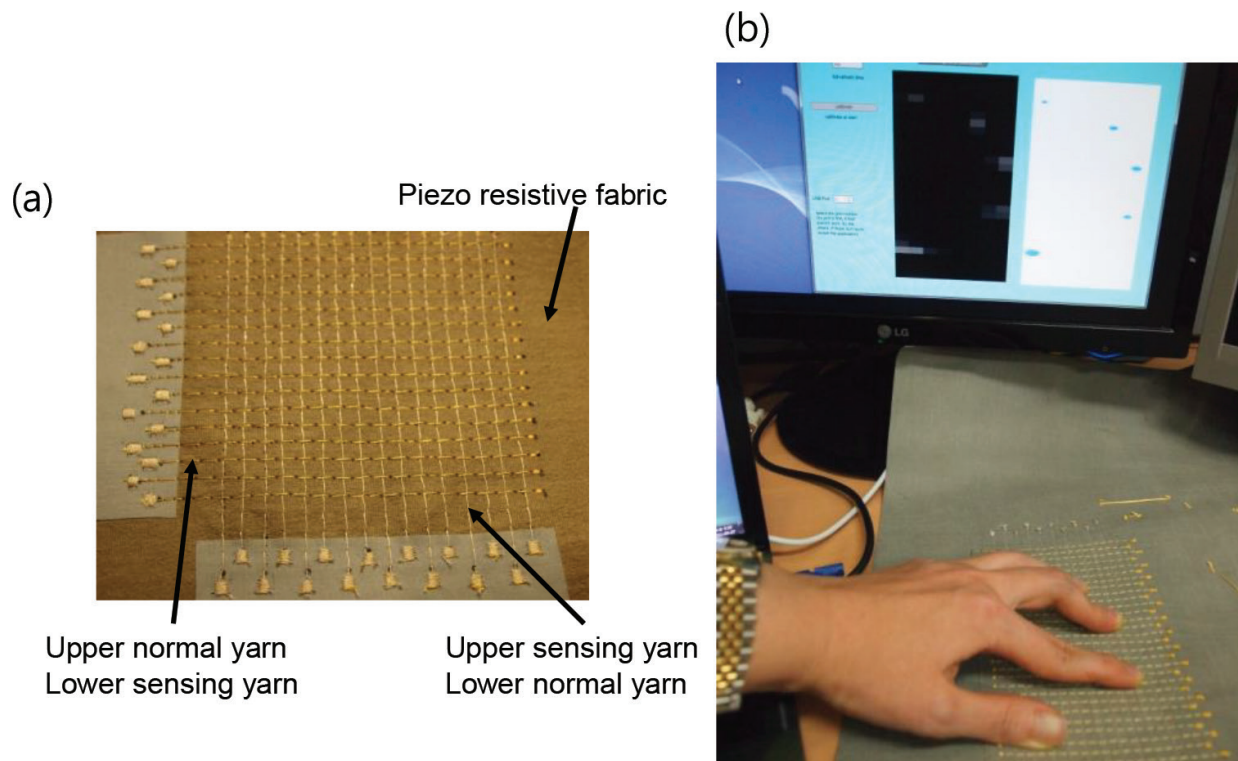


Figure 6. Multitouch and pressure sensing textiles using MCEY embroidery and piezoresistive fabric: (a) prototype of multitouch array sensing and pressure sensing textiles using standard MCEY embroidery and piezoresistive fabric and (b) display that expresses the touched positions and pressure intensities with five fingers.

to capture a vibrato-like gesture well. A standard sewing machine is set up with a conductive MCEY (sensing I or II) top thread and an insulating bottom thread, or vice versa. After one side is completed, the fabric is turned upside down and an orthogonal array of lines is embroidered in [23]. A sandwich structure of MCEY array fabric-Piezoresistive fabric-MCEY array fabric can be proposed for mass production of multitouch and pressure sensing textiles because the MCEY array fabric can be fabricated in large sizes and can be cut freely in various sizes and shapes to meet customer needs.

4. Signal and power transmission applications

4.1. Temperature sensing and heating textiles

MCEY embroidered circuits can be used for signal communication and power transmission in smart textiles systems. **Figure 7** shows the embroideries made with MCEY (signal II) to heat the outdoor jacket [24]. It can be customized to the most appropriate form for each application part of the jacket such as chest, belly, back, neck, ears, and so on. This pure textile component can be easily and unobtrusively embedded anywhere on a garment in any desired shape. It also offers comfort due to its low volume, light weight, flexibility, and breathability.

The thin and flexible MCEY can be embroidered at a distance of about 2 mm, allowing uniform temperature distribution during heating. In addition, since there is a linear correlation between the temperature and the resistance of the MCEY circuit, the MCEY embroidery circuit itself can be used as a temperature monitoring sensor [25]. The temperature of the heated embroidery can be measured by measuring its resistance value in a short time interval.

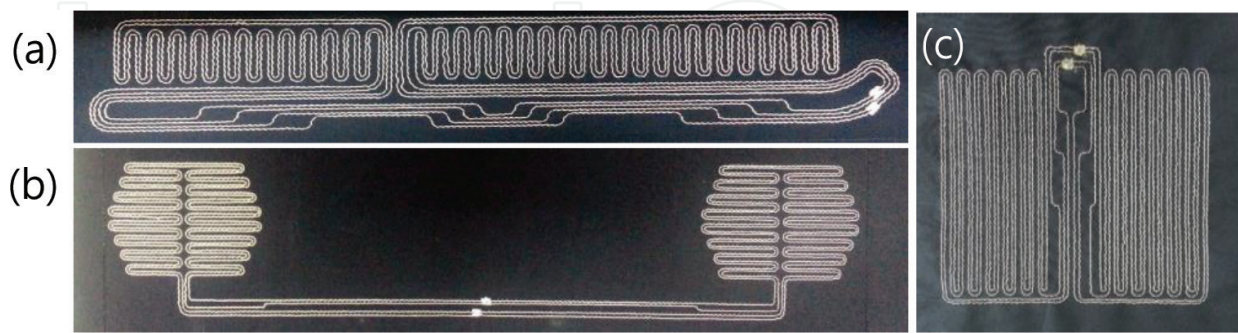


Figure 7. MCEY heating embroideries to be placed on neck (a), ears (b), and back, chest or belly (c) of the outdoor jacket [24].

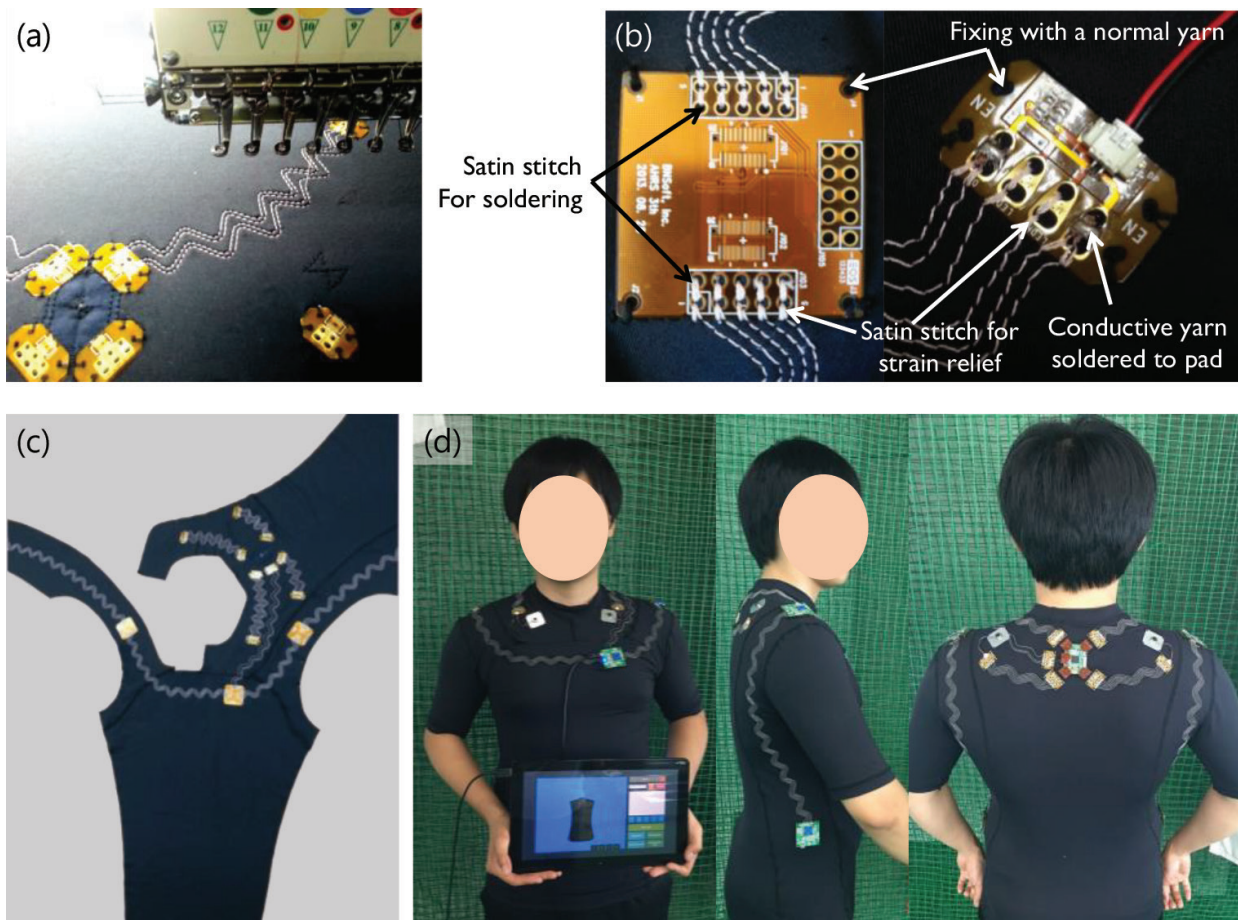


Figure 8. Posture monitoring smart clothing: (a) MCEY circuit patterning process using CNC embroidery method, (b). Embroidered contact with FPCBs on a standard embroidery machine [13], (c) circuit patterning embroidery fabric circuit board, and (d) smart clothing finished by sewing.

A power on–off switching system that refers to real-time-measured temperatures is able to maintain a comfortable set temperatures at all times regardless of changes in internal micro-climate, external climatic conditions, and battery voltage levels.

4.2. Smart clothing for posture monitoring and corrective feedback

To develop “smart clothing” that collects postural data from the sensor and communicate with the host computer in real time, a wearable circuit patterning technique with low resistance and high elasticity is required, along with robust and reliable fabric circuit-sensor interconnection technology. **Figure 8** shows the fabrication process of smart clothing to monitor spine posture and to provide vibration feedback for bad posture. **Figure 8a** shows the process of forming stretchable circuit networks with MCEY (signal II) on a highly stretchable knit fabric (89% polyamide, 11% spandex). FPCBs designed to allow easy attachment and detachment of sensor modules are integrated together during circuit patterning process (**Figure 8b**) [13]. **Figure 8c** shows the fabric circuit board with the circuit patterning process completed on the CNC embroidery machine. Finally, the sensors were mounted on the FPCB to complete the smart clothing (**Figure 8d**).

The design and work order of the smart clothing were designed considering the embroidery process of the 3D wearable circuit networks and the feasibility of garment sewing. FPCB is fixed to the fabric by satin stitch of MCEY (signal II) in hole for fixing and hole for soldering (**Figure 8b**). The FPCB and MCEY embroidered circuit are electrically connected to each other by soldering, while the satin stitch for fixing prevents the strain generated during wearing from being transferred to the soldering connection site.

5. Conclusions

In conclusion, novel metal composite embroidery yarns (MCEYs) have been introduced for touch sensing, textile-based interconnection, signal communication and power transmission for smart wearables. Fabrication methods of the MCEYs and their electrical and physical characterization and circuit patterning and device integration during the CNC embroidery process have been described in detail.

Two methods have been proposed for MCEY fabrication. MCEYs with an electrical resistance of 0.05 Ω /cm showed very low electrical resistance compared with the thickness of the yarn. The electrical resistance of the MCEYs produced by these two methods increases linearly with the increase in length, and if a reinforcing polyester yarn was additionally used at the plying stage (type II method), the uniformity of the electrical resistance of the MCEY embroidered circuit line was greatly improved. As the number of the twisted wrapped yarn of a metal filament and polyester yarn forming the MCEY increases, the electrical resistance of the finally fabricated MCEY will become lower.

Since MCEY has a superfine metal filament covering the surface of the polyester in a spiral shape, it is strong against tensile force, minimizes change of electrical resistance according to elongation,

and is very advantageous for touch sensing. Thus, robust and reliable MCEY embroidered circuits can be applied for sensing, interconnection, and signal and power transmission, and several prototypes have been introduced in this chapter. These examples demonstrate the feasibility and usability associated with the customizability, tailorability, easy and precise circuit formation, and device integration during circuit formation of the MCEY circuit patterning method.

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