Textile Display for Electronic and Brain-Interfaced Communications

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Textile displays are poised to revolutionize current electronic devices, and reshape the future of electronics and related fields such as biomedicine and soft robotics. However, they remain unavailable due to the difficulty of directly constructing electroluminescent devices onto the textile-like substrate to really display desired programmable patterns. Here, a novel textile display is developed from continuous electroluminescent fibers made by a one-step extrusion process. The resulting displaying textile is flexible, stretchable, three-dimensionally twistable, conformable to arbitrarily curved skins, and breathable, and can dynamically display a series of desired patterns, making it useful for bioinspired electronics, soft robotics, and electroluminescent skins, among other applications. It is demonstrated that these displaying textiles can also communicate with a computer and mouse brain for smart display and camouflage applications. This work may open up a new direction for the integration of wearable electroluminescent devices with the human body, providing new and promising communication platforms.

Display technologies have witnessed a revolution in recent years, progressing from black-and-white to colorful liquid crystal and touch displays.\textsuperscript{[1–5]} Besides enhancing the electroluminescent properties of displays, much effort has been also focused on their flexibility.\textsuperscript{[5–7]} Recently, it is realized that the typical planar architecture of a display may be unsuitable for the flexible electronics in a variety of rapidly developing fields such as portable electronic facilities and soft robots.\textsuperscript{[8,9]} For a planar display to be flexible, it is typically made very thin but this also means they break easily upon deformation.\textsuperscript{[10–13]} Furthermore, with planar displays, it is difficult to achieve 3D twistability for irregular and curved surfaces, and breathability for wearable and biomedical applications.

These issues may be simultaneously resolved by making textile displays that are bendable, twistable, and even stretchable. The thin and networked textile structure may also make them lightweight, wearable and breathable, fitting the contours of our bodies perfectly, which is promising for a wide range of applications besides the abovementioned fields.\textsuperscript{[14–17]} However, it remains challenging to produce such highly desired textile
displays due to the difficulty in directly constructing electroluminescent devices onto the rough textile substrate with high performance.\cite{18-21} Here such a novel textile display has been made from super-stretchable electroluminescent fibers (SEFs) that are prepared by a continuous one-step extruding process. Compared with the planar counterparts, besides the above advantages, the textile display has been also conveniently and efficiently integrated to communicate with the external signal terminals, i.e., the computer and the brain for the booming soft and smart electronics and robotics.

The fabrication of the SEFs is schematically shown in Figure 1a. The outer electroluminescent layer and two inner parallel hydrogel electrodes (Figure 1b) were simultaneously extruded through a custom-designed needle (Figure S1, Supporting Information) by three injection pumps. The SEFs were collected on a rotating roller that moves along the axial direction synchronously with the extrusion of the fibers to prevent them from sticking together (Movie S1, Supporting Information). The resulting fibers were uniform along the axial direction, and their diameters can be typically controlled from micrometers to millimeters by tuning the inner diameter of the custom-designed extruder. Figure 1c represents a cross-sectional scanning electron microscopy (SEM) image of one SEF. The electroluminescent layer consisted of ZnS powder and silicone elastomer that serves as both the protecting layer for the SEF and dielectric layer for electroluminescence.\cite{22} The two ellipse-shaped hydrogel electrodes were designed to increase their face-to-face areas for generating more light.
We used a polymer hydrogel based on poly(vinyl alcohol) and poly(ethylene oxide) for the inner conducting electrodes because they are transparent (with >92% optical transmittance at the wavelength range of 400–850 nm (Figure S2, Supporting Information)), flexible, and stretchable.[23–25] The electrodes can be stretched as high as 800% with a reversible stretching strain of 300% and ionic conductivity reaching close to 0.29 S cm\(^{-1}\) (Figures S3 and S4, Supporting Information). The electrical resistivity of the hydrogel was independent of deformation and increased with increasing strain according to the equation \(R/R_0 = \lambda^2\), where \(R_0\) and \(R\) represent resistances before and after stretching to \(\lambda\) times of its initial length (Figure S5, Supporting Information), respectively.[4,26] This resistance increased much slower under stretching than most commercial stretchable conductors such as silver nanowires, conducting polymers, and carbon nanomaterials. Resistance varied below 4% after stretching for 1000 cycles at 300% strain, demonstrating a high stretching stability (Figure S6, Supporting Information). Obviously, our hydrogel electrodes demonstrated much higher stretchability and optical transparency than the other traditional stretchable electrodes (Table S1, Supporting Information), which is a kind of promising stretchable electrode materials. In addition, although there existed many research works on hydrogel electrodes with high performances, they cannot match our electroluminescent devices. This is because the sectional area of the hydrogel electrode in our device is very small, and the previous hydrogel in this size cannot well crosslink due to many possible reasons, such as oxygen inhibition and dimensional limitation. If you add the accelerator into the hydrogel solution to contribute to its crosslinking, the crosslinking time of the hydrogel is very fast and cannot have the enough time to extrude them into the fiber device. Meanwhile, the added accelerator will prevent the curing process of the outer silicone elastomer layer. Therefore, we have developed the hydrogel electrode based on polyvinyl alcohol and poly(ethylene oxide), the polymerization process of which can be easily controlled after the one-step extruding process. Table S2 (Supporting Information) further systematically compares the performance between our hydrogel electrode and the other previously reported hydrogel electrodes. From the comparison, we can see that our hydrogel electrode demonstrated much higher ionically electrical conductivity with stable stretching stability.

Under an alternating electric field, the charge carriers within the electroluminescent layer of the fibers are accelerated. This enhances the excitation of the luminescent center and generates electron–hole pairs, which upon recombination emits light.[27] Figure 1d shows the luminescence curve of the SEF at different electric fields. Due to enhanced excitation of the luminescent center at increasing electric fields, luminescence was seen to increase from 0.1 to 21.3 cd m\(^{-2}\) when electric field increased from 1 to 7.7 V \(\mu\)m\(^{-1}\). The relationship between luminance and voltage agreed well with the equation \(L = L_0 \exp(-\beta V^{0.2})\), where \(L\) is luminance, \(V\) is applied voltage and both \(L_0\) and \(\beta\) are constants.[29] Additionally, luminance of the SEF increased from 21.3 to 233.4 cd m\(^{-2}\) when ZnS content increased from 10% to 40%. With the further increase in the ZnS content, the mechanical property of the SEF may be significantly decreased although the luminance would be slightly increased. The relationship between luminance and the frequency of the applied voltage was also investigated; maximum luminance appeared at 2500 Hz (Figure S7, Supporting Information). At frequencies lower than 2500 Hz, the generated power was lower, while at higher frequencies, electrons and holes could not combine effectively with each other. The power consumption of the 1-cm-length SEF was approximately 10.5 mW at an electric field of 2.3 V \(\mu\)m\(^{-1}\).

Due to the unique fiber shape, the SEF can emit light in all directions. We measured the relative luminance distribution around the fiber circumference using the instrument shown in Figure S8 (Supporting Information). The two ends of the SEF were fixed by two gears that rotated clockwise, and luminance was measured as the rotating angles increased from 0\(^\circ\) to 360\(^\circ\) at 10\(^\circ\) increments. Highest luminance appeared at the testing angle of 0\(^\circ\) and 180\(^\circ\), which coincided with the highest optical transmission of the two hydrogel electrodes (Figure 1e). This electroluminescent behavior was further verified by simulating the distribution of electric field within the SEF (Figure 1f). The electric field covered the entire SEF but was strongest between the two hydrogel electrodes. The ZnS distribution within the electroluminescent layer was uniform, so the simulated optical field around the SEF was further achieved (Figure 1g; Figure S9, Supporting Information). The optical transmission of the hydrogel was much higher than the electroluminescent layer (Figure S10, Supporting Information), so the most light was absorbed when propagating at the angles of 90\(^\circ\) and 270\(^\circ\) (Figure S11, Supporting Information). The simulation results were consistent with the experiments.

For SEF that are meters in length (Figures 2a; Figure S12, Supporting Information), luminance varied below 5% along the axial direction (Figure S13, Supporting Information). Although green light was primarily shown, other colors such as blue and yellow SEF were also realized by choosing the desired ZnS powders (Figure 2b,c). According to the CIE 1931 standard color-matching functions, the emitted green, blue, and yellow light can be demonstrated by \(x, y\) chromaticity coordinates (0.16, 0.42), (0.15, 0.16), and (0.54, 0.45), respectively (Figure S14, Supporting Information). In addition, many more colors, such as sky blue, red and white, can also be achieved by adding organic fluorescent dyes into the desired ZnS powders.[28] Different colors of SEF (such as green and blue shown in Figure 2d) can be further twisted together. When luminance from both fibers was high enough, the emitted composite light from the twisted SEF gradually became uniform (Figure 2e,f; Figure S15, Supporting Information).

The SEF could be stretched 800% (Figure 2g). Fiber luminescence was fully recoverable at 300% strain (Figure S16, and Movies S2 and S3, Supporting Information), and remained unchanged after 100 cycles (Figure S17, Supporting Information). This is because the hydrogel electrode cannot be fully recovered when the strain exceeded 300%, which may be solved by optimizing the material components. Note that the maximal strain was affected by the ZnS content, and the decreased mechanical strengths with more ZnS decreased the maximal strain (Figure S18, Supporting Information). The maximal strain was decreased from 890%, 750%, and 680% to 570% when ZnS mass percentage increased from 10%, 20%, and 30% to 40%, and the corresponding maximal luminance was increased from 22.4, 65.6, and 133.6 to 242.6 cd m\(^{-2}\).
(Figure S19, Supporting Information). When strains increased from 0 to 800%, luminance ratio after and before stretching increased from 1 to 2.9 (Figure 2h). This increase in luminance ratio is attributed to two interrelated factors: (i) the decrease in the electroluminescent layer thickness resulted from the stretching produced stronger electric fields; and (ii) the increase in the electroluminescent area resulted in a lower areal number density of ZnS phosphor powders (a lower areal number density of ZnS phosphor powders resulted in decrease of luminance ratio). Here the former factor may play a more important role.\(^{[22]}\) The SEF can also effectively emit light in liquids such as silicone oil, which is promising for its application in humid or other rugged environment (Figure S20, Supporting Information). In order to better adapt to the practical applications, a further encapsulation with a protection layer, e.g., silicone and polydimethylsiloxane, can make it washable and do not break during use.\(^{[29,30]}\)

These SEFs were then woven into stretchable textiles for displays (Figure 3a; Figure S21, Supporting Information), and the resulting electroluminescent textile can also be three-dimensionally twisted without compromising the luminance (Figure 3b). The flexibility of our displaying textiles (Figure S22, Supporting Information) was then compared with those of previous reports on wearable electroluminescent displays (Table S3, Supporting Information). They could be further woven with commercial fiber materials such as wool (Figure 3c) using a weaving machine (Figure S23, Supporting Information) to produce clothing with patterns such as “F,” “D,” “U” and a smiley face (Figure 3d–g). The color of the displaying textile can be easily adjusted by weaving different colors of SEFs with the help of the circuit design (Figure 3a,c). Patterns with different luminance can be created accurately by manipulating the applied electric field (Figures S24 and S25, Supporting Information). Furthermore, the electroluminescent textile may dynamically (Movie S4, Supporting Information) change the output labels such as numbers from 0 to 9 (Figure 3h). We first wove a long SEF with the commercial wool into an electroluminescent textile with a pattern of “8” (Figure S26, Supporting Information), which was then separated into seven parts so that they can be separately controlled by a controller board and powered by an external energy supply (Figures S27–S29, Supporting Information). The above displaying functions were
also efficiently controlled by the connected computer for smart electronics. The electroluminescent textile was connected to a computer through a relay and a controller board, and displayed an output number of “4” based on a signal from the computer (Figure 3i). We can continuously input different numbers into the computer, resulting in a synchronous dynamic display within the electroluminescent textile (Movie S5, Supporting Information). For wearable applications, the comfortability of the displaying textile should also be carefully considered. Due to the unique textile structure, this displaying textile was lightweight (the weight density of the SEF was 1650 mg m\(^{-1}\)) and possessed good breathability and wet permeability. The weaving patterns of the displaying textile could be further designed to optimize the mechanical properties of the textile, so that the textile can be prevented from damaging during use and more comfortable for the human body. The temperature of the displaying textile was maintained below 24 °C (room temperature of 23 °C) even after continuously working for 5 h (Figure S30, Supporting Information). Although the current displaying textile needs an external power source, with the rapid advance of wearable energy storage devices such as fiber-shaped lithium-ion batteries and wearable nanogenerators, the SEF may be integrated with them to realize self-powering functionality.[31]

In addition to different patterns, the electroluminescent textile could also display different colors. For some organisms such as the chameleon, survival depends on their ability to disguise themselves through camouflage (Figure 4a).[32,33] However, most animals and human beings are not capable of changing colors to match their surrounding environment like chameleons do. Instead, they use their eye as a light detector to transmit light information to the image-forming visual areas of the brain including the primary visual cortex (V1), to extract color information from the environment. We mimicked the chameleon in using the brain to control the color of the electroluminescent textile. Figure 4b illustrates the integrated brain-interfaced camouflage system that decodes color information from visual responses in the brain to drive the electroluminescent textile. Light intensities from blue and green light-emitting diodes (LEDs) were similar (\(\approx 0.25 \mu W \text{ mm}^{-2}\)). Hence the neurons that we recorded were sensitive only to the difference in

Figure 3. Textile displays based on the SEFs. a,b) Electroluminescent textile being gradually stretched from 0, 53%, and 113% to 207% (a) and twisted by hand (b). c) An electroluminescent textile created by weaving SEFs and commercial wool together using a weaving machine. d–g) Display textiles containing different patterns. h) An electroluminescent textile displaying numbers from 0 to 9. i) Electroluminescent textile showing a designed number controlled by computer. A number of “4” was input into the computer, which was detected and transferred to the electroluminescent textile by the controller board and relay. The output number of “4” was displayed on the textile. Scale bars in a, d, g, and h: 1 cm.
color. Spiking activities recorded from single neurons in V1 using a multichannel acquisition system reflect the brain-coded visual information. A neural decoder translates the V1 activities in real time into command signals for an external driver that subsequently delivers ON and OFF signals to the electroluminescent textile (Figures S31 and S32, Supporting Information).

To support the development of the brain-interfaced camouflage system, we first explored the color encoding of V1 neurons in a standalone electrophysiology experiment. The mouse visual system is dichromatic, possessing short-wavelength (such as UV and blue light) and middle-wavelength (such as green light) opsins in the retina.\textsuperscript{34,35} To record the spiking activities from neurons, one 16-channel microelectrode array was implanted into V1. 20 min after implantation, spiking activities (40 kHz) recorded from V1 neurons displayed transient selectivity between blue and green light ($BGI = 0.314$, Figure 4c). We developed a decoder that calculated two thresholds to differentiate blue and green light responses from baseline activity (Figure S33, Supporting Information). The reliability of the decoder was 1 Hz. Evaluations of
the decoder showed a 78% correct rate (22 neurons of 9 mice) in real time over extended periods of at least 150 s. Based on the statistics in these neurons, stochastic changes in the brain did not undermine the performance of the decoder. Further efforts are needed to identity neurons with larger BGI.

We next exploited our integrated platform to implement a brain-interfaced camouflage system wherein the decoded neuronal responses determined the color of the electroluminescent textile (Figure 4d,e). Without prior exposure to the surrounding light, we tested the color responses of the recorded neurons from a naive mouse in a 40 s training session by turning on the green and blue LEDs alternatively, in which spikes were sorted and selected as a color-selective neuron after chromatic selectivity analysis (Figure S34a, Supporting Information). We then made a spike template from the color-selective neuron and calibrated the decoder with the thresholds generated from the chromatic selectivity analysis (>7 Hz for green light and 2–7 Hz for blue light, Figure S34b, Supporting Information). In the online session, we used the spike template from the training session for real-time spike sorting and decoding. Brain-controlled electroluminescent textile responded immediately after the surrounding light switched between green and blue color (Figure 4d; Figure S35a and Movie S6, Supporting Information). The correct rate for this on-line session was 85.7%. The average reaction time for the electroluminescent textile was 0.44 s, which is due to the delay in neuronal response to the onset of light (0.04 s), neuronal activity recording and decoding (0.18 s), command communication between the decoder and the driver (0.18 s) and time to turn on the SEFs (0.04 s) (Figure S35b, Supporting Information). These results revealed evidences for the proof-of-concept brain-interfaced camouflage, providing an effective strategy in developing smart electronic textiles.

We have realized a novel displaying textile, which possesses the unique advantages of typical clothes such as flexibility, stretchability, twistability, and conformal attachment to the contours of our bodies and arbitrarily curved skins coupled with breathability. It can dynamically display the desired patterns by inputting the signal into the terminals such as computer and brain for smart displaying. This work may open up a new direction at the integration of the wearable electroluminescent devices with the human body for providing new and promising communication platforms.

**Experimental Section**

All details of methods and associated references can be found in the Supporting Information.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

brain-interfaced communications, electroluminescent fiber, textile display

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