Simultaneous Sensing of Touch and Pressure by Using Highly Elastic e-Fabrics

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Abstract: In recent years, electronic skins have been widely studied for human monitoring systems. This research field needs multi-sensing points for large deformation, strong recovery, and mass production methods. Toward these aims, the fabrication of e-fabric skins made from a capacitive touch sensing layer and a capacitive pressure sensing layer is presented in the paper. Due to the high elasticity of the dielectric layer of the spacer fabric, this structure exhibits a very fast recovery time (6 ms), low hysteresis (<5%), and high cycling stability (>20,000 times). Besides, the stacking structure of the electrode layers (single-wall carbon nanotube/silver paste) is due to good durability even under large deformations (grasping, bending, stretching), and the skin is breathable for applications. As expected, the e-fabric skin is proven to be robust for detecting a spatial pressure distribution in real time. The extremely simple fabrication process is also an extra plus point in view of point mass production.

Keywords: e-fabric skin; stretchable silver paste; single-wall carbon nanotube (SWCNT); screen printing; capacitive pressure sensor

1. Introduction

In recent years, electronic skins (e-skins) for wearable systems have attracted a lot of attention from researchers [1,2]. There have been many studies on the design and fabrication of e-skins with functionalities and mechanical properties comparable to natural skin in soft robotics [3–7], human physiological monitoring, health care [8–11], and human–machine interfaces [12–16]. Most of the mechanisms of skin-like electronics are based on a relationship between pressure and electrical properties such as the resistance [17,18] and capacitance [19–22] of constituent conductive materials. To date, capacitive soft sensors have dominated research in this field due to good performance and better stability than resistive soft sensors. According to these principles, many e-skin studies have been reported; Kim et al. [23] developed stretchable silicon nanoribbon electronics for a skin prosthesis. Zou et al. [24] studied the development of a re-healable, recyclable, and malleable electronic skin based on a dynamic covalent thermoset nanocomposite. You et al. [25] presented an e-skin tactile sensor matrix pixelated by position-registered conductive microparticles. Ronghui et al. [26] researched a textile electronic skin enabled by a highly elastic spacer fabric and conductive fibers. However, limitations still exist in such studies such as insensitivity under touching without pressure, too high a sensitivity for large pressure applications, limited air permeability, or complex fabrication. In order to fulfill these aims, we propose a hybrid approach for e-fabric skin by combining screen printing and heat transfer techniques. The design of the e-fabric-like skin is based on the structure of multi-line capacitors with two main layers, which are composed of SWCNT/stretchable silver paste [27–32] as electrode layers and special-structure fabrics as a dielectric layer. The resulting e-fabric-skin has high flexibility, is breathable, lightweight, and has easy integration into clothing. The CNTs are toxic for the skin, but it will be covered by silver paste. To the knowledge of the authors, the
toxicity of silver is very low, and there are no materials cheaper than and least harmful to the skin as silver [33] in order to make the electrode materials. More importantly, the SWCNT/stretchable silver paste material can increase the durability strongly needed in applications such as bending, stretching, or twisting. In addition, the special structure of the fabrics will not only protect the e-fabric skin under a large deformation (1000 kPa), but also ensure a fast response–recover time (<6 ms). In this work, we explored the feasibility of using spacer fabrics to achieve high repeatability and hysteresis-free pressure responses in the flexible capacitive pressure fabric systems. The manufacturing process, as shown in Figure 1, allows for rapid, reliable, and scalable production of large sensor sheets. As this process just focuses on printing the layers, it is simpler than other existing works [26,34]. Otherwise, the screen-printing technologies are easy to approach and apply in industry. The fabrication method demonstrated the possibility of mass production for wide applications in soft robotics, health monitoring, human motion tracking, or prosthetics devices.

**Figure 1.** The manufacturing process of capacitive pressure sensor consisting of (a) preparing SWCNT ink and silver paste, (b) printing SWCNT rows of the capacitive sensor layer, (c) printing silver rows of the capacitive sensor layer, (d) printing the separation films at the cross-nodes of the capacitive sensor layer, (e) printing SWCNT columns of the capacitive sensor layer, (f) printing silver columns of the capacitive sensor layer, (g) the final capacitive sensor layer, (h) printing SWCNT rows on the top side of the capacitive-pressure sensor layer, (i) printing silver-rows on the top side of the capacitive-pressure sensor layer, (k) printing SWCNT columns on the bottom side of the capacitive-pressure sensor layer, (l) printing silver columns on the bottom side of the capacitive-pressure sensor layer, (m) the final capacitive-pressure sensor layer, (n) creating e-fabric-skin by combining the capacitive sensor layer and the capacitive-pressure sensor layer, (o) cross-section of the e-fabric-skin, and (p) application of the e-fabric-skin.

2. Materials and Methods

2.1. Materials

The polyester/spandex (PET/SP) fabrics were made by co-weaving spandex with polyester. The PET/SP spacer fabrics were placed by connecting two independent PET/SP fabric layers with a spacer layer (PET yarns) so that the fabrics had a three-dimensional structure. The structure of the PET/SP layers was composed of conventional PET/SP multifilament yarns with high elasticity and recovery. These fibers could be converted into conductive fibers via soaking, padding, and surface treatment.
Thus, the PET/SP fabrics and PET/SP spacer fabrics are very resilient, can withstand harsh levels of wear and tear, and are waterproof and show less wrinkling.

In the research, we used the SWCNT ink and the stretchable silver paste in order to produce electrode lines on the fabrics. The SWCNT ink was prepared from KH Chemicals Co. Ltd., Seoul, Republic of Korea [35], and the stretchable silver paste was obtained from Dycotec Materials Ltd., Swindon, United Kingdom [36]. We used screen-printing technologies in order to apply SWCNT and silver paste on the PET/SP fabric and PET/SP spacer fabric, respectively. The silver paste layer helps the e-fabric skin to have conductivity, stretchability, recovery, and flexibility in a wearable device application. Besides, the SWCNT layer would guarantee constant and robust conductivity of the sensor structure under large deformations.

2.2. Fabrications of the Sensor Layers

The manufacturing process of the e-fabric skin-based soft capacitive pressure sensor is shown in Figure 1. The process consists of three main steps: (1) Preparation of the SWCNT ink as a conductive buffer layer and the stretchable silver paste as a conductive layer (Figure 1a), (2) using screen-printing technologies in order to fabricate the capacitive sensor layer based on the PET/SP fabric and the capacitive pressure sensor layer based on the PET/SP spacer fabric, and (3) integrating two fabricated layers with the robust electrical connections in order to complete the e-fabric-skin.

In the first step, the SWCNT ink 0.1 wt.% (the weight percent of single-walled carbon nanotubes in water) was stirred and ultra-sonicated (2 h, 19.990 Hz) in a stirring machine (60–80 °C, 1000 rpm, 24 h), and the silver paste was stored in a fridge (4 °C) with the lids tightly sealed. The used fabric was a polyethylene terephthalate/spandex fabric with a 76/24 (76% polyethylene terephthalate, 24% polyurethane) ratio from SNT Co. Ltd., Seoul. The stretchable paste would be gently stirred before use to avoid incorporation of air bubbles. The PET/SP spacer fabrics have 3D manufactured textile structures in which two outer textile layers (PET/SP fabric layers) are connected by a layer of pile fibers (PET). The design of the construction has the properties of good breathability, crush resistance, pressure stability, and 3D appearance.

In the second step, the SWCNT ink and silver pastes were applied on the PET/SP fabric (Figure 1b–g) and the PET/SP spacer fabric (Figure 1h–m) by screen-printing technologies at a speed of ~30 mm/s with the printing tools, as shown in Figure S1 (Supplementary Materials). After printing the SWCNT layer, excess water in the fabrics was removed by the two-way drying machine. The drying conditions were set-up at the time of drying of 1–3 min, range of temperatures of 180–200 °C, and speed of the circulation fan of 1500 rpm. After printing the silver paste layer, the stretchable silver paste was dried, before curing, at 60–80 °C for 15 min to remove solvents in an IR or convection oven. The curing parameter used was 120–200 °C for 10 min.

Finally, using a thin adhesive layer and a heat press in order to integrate two sensor layers together (Figure 1n), and to laminate the electric lines onto the surface, robust electrical connections were attained. Figure 1o,p show an actual image of the two sensor layers, as well as the application of the e-fabric-skin on the hand.

3. Experimental

3.1. Structure

3.1.1. The Capacitive Touch Sensor Layer

The working principle of the capacitive sensor layer used is based on projected capacitive technologies [37–39]. This technology detects touch actions by measuring the capacitance at each addressable electrode. The projected capacitive layer formed by a charged matrix (4 × 4 electrodes) has been designed. This sensor layer has been developed with two conductive layers for horizontal and vertical tracks and a layer of dielectric. Three patterns are shown in Figure 2a, consisting of a vertical or capacitive column layer (silver paste/SWCNT), horizontal or capacitive row layer (silver paste/SWCNT), and a dielectric layer (PET/SP fabric). The diamond structures have been selected for
the capacitive touch layer with a pitch of 14 mm and gap of 2 mm. At the nodes, the row-column electrodes are separated by an elastic thin film with 100% polyurethane (PU), and the thickness is 10 μm. Figure 2b shows a real image of the final capacitive sensor layer, and Figure 2c shows the electrical response of the capacitive sensor under the touch of a finger. It is clear that the capacitance change at every individual point on the grid can be measured to accurately determine the touch location by measuring the voltage in the other axis (rows-columns).

Figure 2. (a) Structure of the capacitive sensor layer, (b) real picture of the capacitive sensor layer, and (c) working principle of the capacitive sensor layer.

3.1.2. The Capacitive Pressure Sensor Layer

Figure 3a shows the structure of the capacitive pressure sensor layer, consisting of a vertical or capacitive column layer (silver paste/SWCNT) on the top side, a dielectric layer (spacer fabric), and a horizontal or capacitive row layer (silver paste/SWCNT) on the bottom side. The column structures have been selected for the capacitive pressure layer with a width of each sensing plate (column/row) of 12 mm, and a gap between two plates of 5 mm. These dimensions/resolutions of the two sensing layers were chosen in order to easily make the prototype samples. In the screen-printing technologies on the fabric, the smallest size of each electrode line should be about 0.1 mm to ensure the working performance, but it needs more experiments to obtain the final size. Figure 3c shows the electrical response of the capacitive pressure sensor layer under the pressure of a finger. When the spacer fabric is under pressure, the spacer layer (PET yarns) is bent from the stretching state. When the pressure is released, the spacer layer returns to the initial state. The pressing position could be detected by the capacitive change between the column layer on the top side and the row layer on the bottom side.

At the pressing point, the capacitive pressure sensors are based on the principle of parallel-plate capacitance [40–42]. The capacitance is accordingly varying as a function of changes in the distance between parallel-plate electrodes (Figure 3d). In wearable applications, the design of the capacitive pressure sensors is difficult by the low elasticity of the materials. Otherwise, the outputs are easily influenced by parasitic capacitance. The spacer layer, by PET yarns of the spacer fabric, will improve the elasticity of the electrodes, thereby increasing the sensitivity of the sensor for flexible applications in wearable research [26,43,44].
Figure 3. (a) Structure of the capacitive pressure sensor layer, (b) real picture, (c) working principle of the capacitive pressure sensor layer, and (d) working principle at the sensing point.

The capacitance at the pressing point (C) can be calculated by Equation 1, where A represents electrode area, d represents dielectric thickness, \( \varepsilon_0 \) represents a constant for the dielectric permittivity of vacuum, and \( \varepsilon_r \) represents the permittivity of a dielectric. Following that, the capacitance change relies on the change in dielectric thickness of the spacer fabric.

\[
C_{\text{sensor}} = \varepsilon_0 \varepsilon_r \frac{A}{d_0}
\]  

(1)

The variations in the permittivity of dielectric layers also contribute to a change in capacitance, as shown in Equation 2, where \( \varepsilon_{\text{air}} = 1 \) and \( \varepsilon_{\text{PET}} = 3.3 \). The sensitivity increases when the volume of the air gaps decreases. The decrease in dielectric thickness (d) and increase in permittivity (\( \varepsilon_r \)) under pressure together contribute to the increase in the sensitivity of the textile capacitance sensor.

\[
\varepsilon_e = (\%V_{\text{air}} \cdot \varepsilon_{\text{air}} + \%V_{\text{PET}} \cdot \varepsilon_{\text{PET}})
\]  

(2)

3.2. Results and Discussion

3.2.1. Characterization of the e-Fabric Skin

Figure 4 shows scanning electron microscope (SEM) images of the standard spacer fabric with the magnified view showing the initial yarns, and the printed yarns with SWCNTs/silver at different steps of the process proposed. The diameter of the single PET yarn is about 10 \( \mu m \) and appears loosely twisted with ample free space between the microfibers, as shown in Figure 4a,d. SWCNT particles could be observed in the form of thin printings, which stuck randomly onto the PET/SP yarns with a 50% printing area (Figure 4b,e). Otherwise, the silver conductive layer was printed onto CNTs-PET/SP yarns with a 95% printing area, as shown in Figure 4c,f.
In order to analyze the electrical response of the proposed multi-structure sensor (capacitive pressure sensor layer), we developed an experimental setup in order to test sensor data using a customized universal testing machine (UTM machine, South Korea), as shown in Figure 5a. Figure 5b shows the sensitivity (S) of the capacitive pressure sensor under applied pressure levels from 0 to 100 kPa. The sensitivity of the pressure sensor can be expressed as $S = \frac{\Delta C}{C_0/P}$, where $\Delta C$ represents the change in capacitance ($C - C_0$), $C_0$ is the initial capacitance with no pressure, and $P$ represents the pressure load. There are two slopes based on 60 kPa. The pressure sensitivity is $93.3 \times 10^{-4}$ kPa$^{-1}$ at 60 kPa and $205 \times 10^{-4}$ kPa$^{-1}$ at 100 kPa. This value depends on the level of pressure. Otherwise, Figure 5c,d show the relative change in the capacitance and compression distance under pressure from 0 to 1000 kPa. These results demonstrate a large working range of the sensors under high pressure (up to 1000 kPa). At the 1000 kPa pressure level, the output signals of the sensing points were still below the saturation point. However, the sensitivity values of the sensors reduced at this level. From the relative change in the capacitance under pressure levels, it is clear that this structure ensures the sensitivity and the working range of the sensors. Besides, Figure 5e also shows the breathable ability of this structure that is impermeable to water and permeable to air. Figure S2 (Supplementary Materials) demonstrates the test method for determining the breathability of the sensors. The sample was kept on the hand for 5 h. This skin area was not itchy or discolored when compared to the skin area nearby.
Response/recovery time are important parameters for evaluating the performance of the sensor in the dynamic application. The viscoelastic nature of the PET yarns of the spacer fabric is the main reason for a delay time. Figure 5f shows a fast response/recovery time of 6 ms at 100 kPa. Due to the fast self-recovery process of the PET connections, our sensors demonstrate the rapid recovery of the electrical property and ensures the performance of the device during high pressure or a lot of working cycles. This advantage is mainly caused by the excellent elastic properties of the PET/SP spacer fabric, especially the release-ability of PET connections between two parallel-plate electrodes of the capacitive pressure sensor points. Response/recovery times and breathable ability become important when the skin-like sensor is used in dynamic applications such as human–machine interfaces [45], soft wearable robotics applications [46], and healthcare [47].

The working performance of the sensors is evaluated through the stable electrical functionality and mechanical integrity during their loading/unloading cycles (dynamic durability). This is mainly caused by the fatigue and plastic deformation of the PET connections under high pressure, which causes damage to the spacer layers and the sensing nanomaterials (silver breads/SWCNTs). The durability was performed under a lab-customized UTM, and the capacitance was measured every 50 cycles. Attributed to the high elastic recovery performance of the spacer fabric dielectric layer, the sensors show an intact sensitivity and is highly reproducible. Uniform capacitive changes of less than 7% were recorded after 10,000 loading/unloading cycles at 100 kPa, as shown in Figure 6a, as well as less than 10% after 20,000 intensive cycles at 1000 kPa, as shown in Figure 6b. It is worth mentioning that the electric fabric sensor also has high durability to other deformation types. Figure 6c,d demonstrate that the conductivity of two electrode layers is almost constant when stretching from 0 to 20%, bending, and twisting at different angles, which is significant for wearable applications. In real applications, sensors often face high stretches and large deformation (Figure 6e).
Figure 6. Characteristics of capacitive pressure sensor consisting of (a) dynamic durability of the sensor after 10,000 loading/unloading cycles at pressure of 100 kPa, (b) dynamic durability of the sensor after 20,000 loading/unloading cycles at pressure of 1000 kPa, (c) resistance change of the sensor when stretching from 0 to 20%, (d) resistance change of the sensor under different deformations, and (e) state of the e-fabric-skin after large deformation.

Figure 7a,b show the effect of environments on the performance of the sensors. The capacitance has a little change in the temperature range from 20 °C to 30 °C, as well as in the humidity range from 40% to 60%. With these sensors, the influence of humidity is slightly higher than that of the temperature. This is likely due to the relative permittivity of the air inside the spacer layer changing with the humidity and temperature. In order to decrease the effect of these factors, we suggest decreasing the volume of the air by injecting silicones or encapsulation paste to the spacer layer. However, this method will also decrease the breathability of the sensor, so it needs more experiments. Textile electronics have a major limitation, that is, the electrode materials (CNTs/silvers) will fall out after washing. Figure 7c shows the capacitance of the sensors at 100 kPa after a number of washing times. It is clear that the sensors can still work well after 50 washing times. This advantage is mainly caused by the adhesive ability of silver pastes in order to protect the electrode materials. Hysteresis is the maximum difference between the output values obtained for the same input value. The small hysteresis properties of the fabricated sensors are shown in Figure 7d, and the maximum error is 5%.
The sensors are evaluated in an overview comparison with other existing works. Our sensors have a sensitivity higher than two studies, (0.283 kPa\(^{-1}\) at 5 kPa) [26] and (121 \times 10^{-4} \text{kPa}^{-1}\) at 100 kPa) [48], and lower than two studies (0.007 kPa\(^{-1}\) at 5 kPa) [34,49]. Our sensors also have a lower thickness than those studies, as shown in Figure 8. Due to using the spacer fabric, the sensors also have better breathable properties than the reference samples in two studies [34] (using aluminum foil), and [48] (using silicone layers). The spacer layers by the PET yarns will also be more highly elastic than the silicone. Besides, it is clear that our sensors showed an excellent working ability at the positions where the large deformations are common. However, the structure still has a limitation with extremely slight pressures. This is due to decreased sensitivity when increasing the number of PET fibers in the spacer layer. We suggest removing a part of these fibers to ensure the sensitivity of the e-skin.

Figure 7. (a) Relative change in the capacitance under temperature from 20 to 30 °C, (b) relative change in the capacitance under humidity from 40 to 60%, (c) the capacitance of sensors at 100 kPa after 50 washing times, and (d) hysteresis of the sensor at 100 kPa.

Figure 8. The thickness of the fabricated sensors in comparison to other studies.

3.2.2. e-Fabric Skin in a Real Application
To demonstrate the potential for the e-fabric skin to be used in a realistic application, the proposed sensor was integrated into a textile structure in order to distinguish different motions with touch, pressure, and multi-touch/pressure of the fingers. Three motions of the fingers for a specified amount of time were made on a sample pad, and the electrical signal of two sensor layers was recorded. Figure 9 and Video S1 (Supplementary Materials) show the capacitance change ratio ($\Delta C/C_0$) of the e-fabric-skin (the capacitive sensor layer and the capacitive pressure sensor layer). The result shows that the structure of this fabricated sensor can be utilized to sense the fingertip touch and pressure during the action. This soft sensor also shows the application ability in the robotic control field.

![Figure 9](image_url.png)

**Figure 9.** Demonstration of e-fabric-skin in the different motions consisting of (a) touch, (b) pressure, and (c) multi-touch/pressure.

4. Conclusions

This research has reported a complete e-fabric skin by combining two sensor layers developed by stretchable silver paste/SWCNT on different fabrics based on screen-printing technologies. The touching action can be detected by the capacitive sensor layer fabricated by the matrix of rhombus lines on one side of the PET/SP fabric. Furthermore, the pressing action can be detected by the capacitive pressure sensor layer fabricated from a matrix of parallel plates on two sides of the PET/SP spacer fabric. The results emphasized the potential of using a regular PET/SP spacer fabric in order to achieve a high repeatability and very fast recovery time of the sensors under large deformations. Finally, we demonstrated the application of the e-fabric skin sensor for the detection of finger motions via the integration of the sensor as a touchpad. Based on the statistical indices and simple fabrication process, we demonstrated that this structure could be used in smart clothing for recognizing human motion or soft wearable robotics applications for control purposes.

**Supplementary Materials:** The following are available online at www.mdpi.com/xxx/s1, Figure S1: The frames and squeegee for printing the samples, Figure S2: Experiment for determining the breathability of the sensors, Video S1: The operation of e-fabric skin in a real application.

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