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Textile-Only Capacitive Sensors with a Lockstitch Structure for Facile Integration in Any Areas of a Fabric

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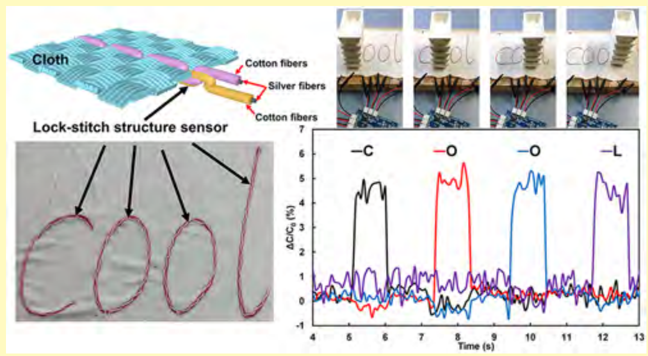
ABSTRACT: A woven structure has been gradually applied in capacitive pressure sensing due to its good performance for fabric integration. However, restricted by the square-cross arrangement of yarns, the woven structure sensors are typically limited to being implemented in rather rectangular areas of a fabric. For nonrectangular areas, a lockstitch structure is shown to be excellent for preparing textile-only capacitive sensors which are based on the conductive core-spun yarns. The lockstitch structure, which is inspired by the stitch type used for sewing, ensures the facile integration of the sensors on the fabric of interest at any position by sewing. The sensors with this novel approach only occupy small spaces, and hence will not affect the overall softness of the fabric at large. Importantly, they show good performance in signaling, sensitivity, stability, and robustness.



KEYWORDS: *capacitive pressure sensors, textile sensors, lockstitch structure, facile integration, nonrectangular areas*

In recent years, wearable pressure sensors have attracted more and more interest because of their marvelous applications such as human motion detection,[1−3] human−machine interaction,[4−6] and long-term continuous monitoring of health.[7−9] To prepare wearable pressure sensors, various types of pressure sensors have been developed such as piezoresistive,[10,11] capacitive,[12,13] piezoelectric,[14,15] and field-effect transistor.[16] Among them, capacitive pressure sensors have extraordinary advantages such as high sensitivity, fast response, excellent stability, and low operating voltage.[17−20]

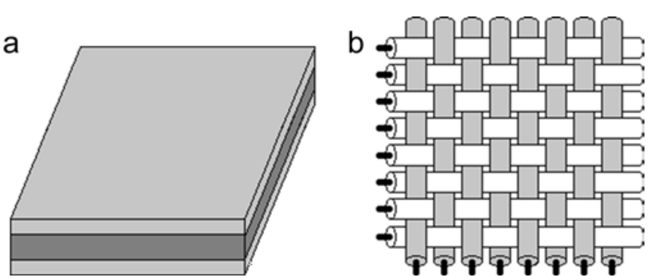


Figure 1. Schematic diagrams of (a) sandwich structure and (b) woven structure in capacitive pressure sensors.

Up to the present, the structures used in capacitive pressure sensors mainly include sandwich structures[21,22] and woven structures.[23−27] The sandwich structure sensors need large planar surfaces and have relatively high thicknesses due to their three-layer structures, preventing the miniaturization of sensors.[28−30] Besides, sandwich structure sensors are typically fixed on body or cloth by multilayering and glueing, with lack

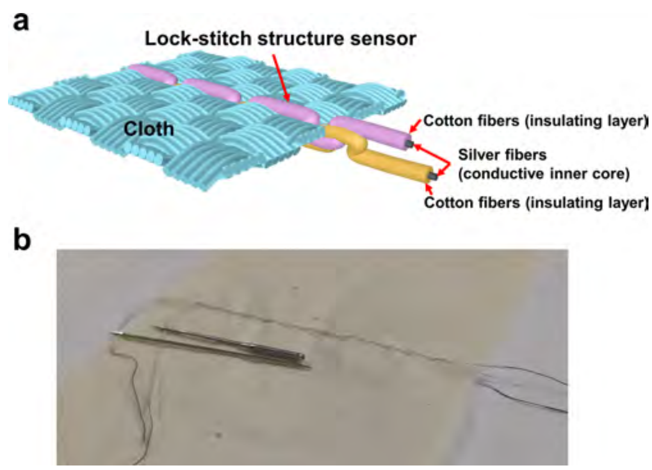


Figure 2. Schematic diagram and photo of the cotton cloth integrated with the lockstitch structure sensor.

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Table 1. Blending Length of Cotton Cloth before and after Adding the Lockstitch Structure Sensor

sample	bending length (cm)
Cotton cloth	1.90 ± 0.05
Cotton cloth integrated with the lockstitch structure sensor	1.98 ± 0.08

of wearability.[31−34] The woven structure pressure sensors avoid these issues, showing good wearability. They can be integrated well in fabric through blending[23] or weaving.[24] However, the shapes of sensors have been limited to rectangles due to the square-cross arrangement of yarns (Figure 1b) in woven structures.[23−27] Therefore, the woven structure sensors are not suitable for the nonrectangular areas of fabric, especially in irregular areas.

In this work, a lockstitch structure was first developed to prepare a textile-only capacitive pressure sensor without restriction of shapes. Compared with conventional sandwich structures, the new structure is more suitable for the fabric sensors and makes them integrate well in clothing. Compared with woven structures, it enables sensors to integrate in any position of the fabric with no shape limit, which solves the issues related to pressure sensing in irregular areas of fabric. The lockstitch structure sensors displayed good performance in sensitivity, response, stability, and robustness. Cotton cloth with irregular sensing regions was demonstrated by sewing the sensors into it, which were then able to detect positions where the objects were placed.

To the best of our knowledge, this work first reports a textile-only capacitive-type pressure sensor with thread-like morphology. Moreover, the fabrication method of the sensor

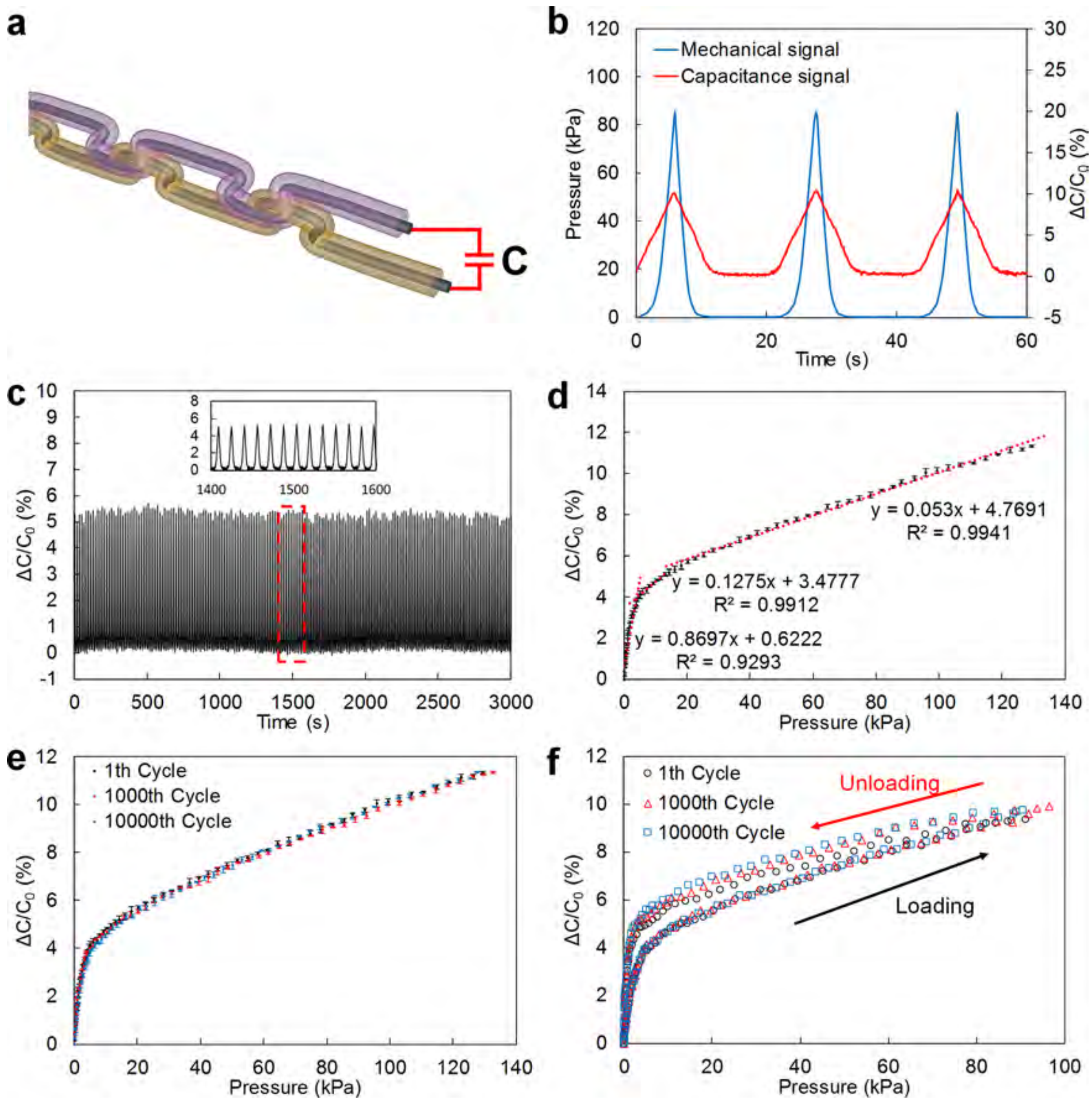

Figure 3. (a) Schematic diagram of the capacitor between two core-spun yarns. (b) Pressure applied on the lockstitch structure sensor and its capacitance signals. (c) Capacitive response of the lockstitch structure sensor to continuous compressions under a pressure of 15 kPa. (d) Relationship between the relative change in capacitance and applied pressure of the lockstitch structure sensor. (e) Pressure−capacitance curves of lockstitch structure sensor after different numbers of repeated cycles. (f) Capacitance change of the lockstitch structure sensor during a consecutive loading−unloading process after different numbers of repeated cycles. Error bars represent the standard deviation of the repeated measurements.

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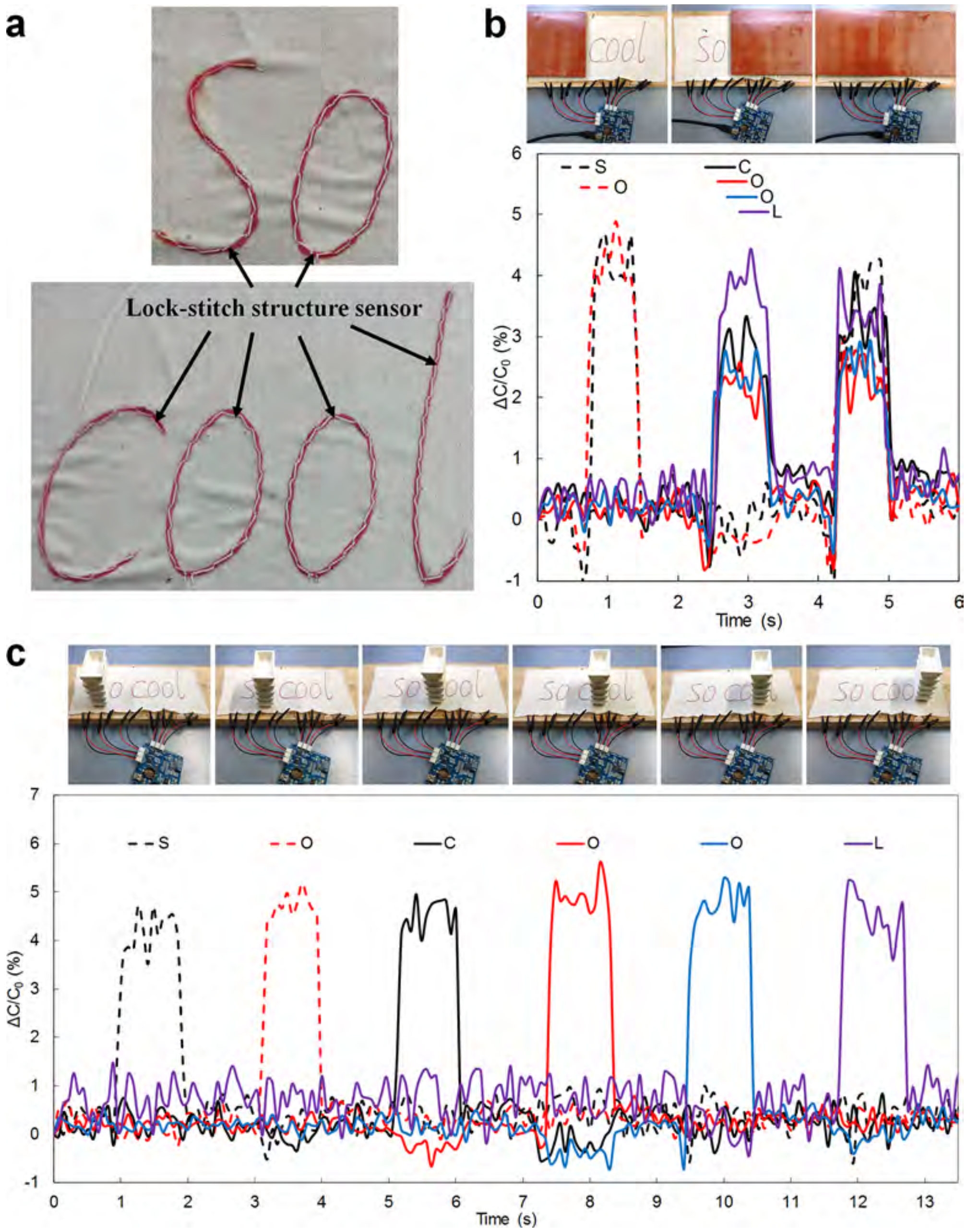

Figure 4. (a) Six lockstitch structure sensors were sewn into the cotton cloth. (b,c) Simultaneously measured capacitances from the six sensors, while the objects were rested upon them.

based on conductive core-spun yarns may help to develop more suitable structures for capacitive wearable sensors.

The lockstitch structure inspired by sewing thread is an often-used type of stitch.[35,36] Hence, the sensors with this structure can be integrated into fabric through sewing, which occupies a small space. As shown in Figure 2, the sensor is composed of two conductive core-spun yarns by interlocking in the cotton cloth. The core-spun yarns were reported in our previous work,[25] and were fabricated by wrapping silver fibers with cotton fibers, and fixed with polyurethane adhesive (see Figures S2 and S3 for details). The core-spun yarn is small in diameter (0.32 ± 0.02 mm), enabling the use of typical sewing needles (Figure 2b). By sewing two core-spun yarns in the cotton cloth (0.25 ± 0.01 mm thickness) according to the lockstitch type, the lockstitch structure sensor was prepared.

The evaluation of textile softness by bending is an ingenious and effective approach.[37,38] The softness of the cotton cloth before and after adding the lockstitch structure sensor was investigated by comparing their bending length (see Figure S5). As shown in Table 1, the similar bending length indicated that the lockstitch structure sensor made little effect on the softness of fabric.

In lockstitch structure sensors, the silver fibers and cotton fibers are used as electrodes and dielectric layers of the capacitive type sensors, respectively (the conductivity characteristics are discussed in Supporting Information). Capacitance is developed between the core-spun yarns as shown in Figure 3a (0.225 ± 0.003 pF/cm). External pressure reduces the distance between the two yarns, leading to an increase in capacitance. Figure S6 describes the capacitance model of the lockstitch structure sensor in detail.

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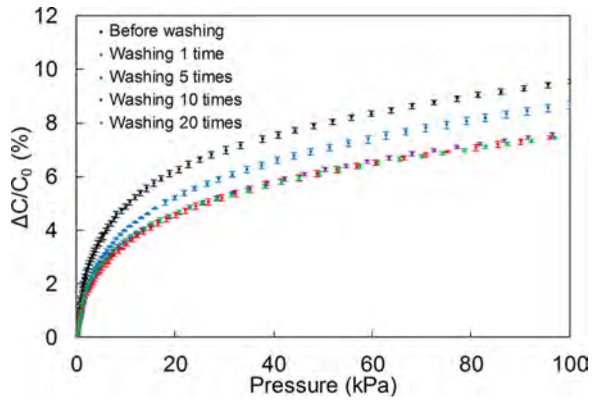

Figure 5. Pressure−capacitance curves of lockstitch structure sensor after washing−drying cycles. After each washing, it is dried, thus making one washing−drying cycle. Error bars represent the standard deviation of the repeated measurements.

Figure 3b shows the pressure applied on a lockstitch structure sensor (linear shape, 6 cm) and its capacitances. As it shows, the sensor responds well to the applied pressures without obvious hysteresis. The output signals of the lockstitch structure sensor are stably maintained without any remarkable degradation in continuous compressions (Figure 3c). Figure 3d presents the capacitive sensing characteristics of the lock-stitch structure sensor. The sensor can withstand a pressure of 130 kPa or more (maximum compression limit was not obtained due to the restriction of texture analyzer). The sensitivity of capacitive pressure sensors, *S*, may be defined as the slope of the traces in Figure 3c.

$$S = \frac{\delta \frac{\Delta C}{C_0}}{\delta p} \tag{1}$$

where p is the applied pressure, and C and C_0 stand for the capacitance with and without the applied pressure, respectively. The sensitivity decreases with the increase of pressure, which is in line with the results of the woven structure sensors reported in other literature.[23−25] For pressures below 4.5 kPa, the sensitivity is 8.697 MPa^{-1}; for those between 4.5 and 14 kPa, the sensitivity is 1.275 MPa^{-1}; while for those above 14 kPa, the sensitivity is 0.53 MPa^{-1}. Compared with previously reported capacitive pressure sensors,[32,33] the sensitivity below a pressure of 14 kPa enables the lockstitch structure sensor to apply in some areas such as artificial skin, tactile sensing, human−machine interaction, etc.

Figure 3f shows the capacitance changes of the lockstitch structure sensor from a consecutive loading−unloading process. A slight hysteresis is observed in the loading−unloading process, similar to the "negligible" amount reported by Lee.[23] Due to the high seam strength from the lockstitch,[35,36] the sensor is tightly blended in the cotton cloth with a stable structure. Hence, the sensor shows a good stability in intensive cycling tests that involves 10,000 repeated compression cycles (maximum pressure is 130 kPa; cycling rate is 12 cycles/min). As shown in Figure 3e,f, there is no significant change in the pressure−capacitance curve, and the hysteresis performance remain stable.

Due to the unique lockstitch structure, the pressure sensor can be sewn anywhere in the fabric. As shown in Figure 4a, six lockstitch structure sensors were integrated in the cotton cloth, with shape of the word "so cool". These sensors formed a sensor array with irregular sensing regions in the cotton cloth, which was difficult to realize in woven structure sensors. Combined with a multichannel measuring circuit proposed in our previous work (Figures S7 and S8),[39] the sensor array was able to measure pressures from six different positions simultaneously. As shown in Figure 4b,c, the positions where the object was rested could be clearly detected. The small size of the sensors made it possible for the incorporation of large number of sensors into wearable devices.

The washability of the lockstitch structure sensor was investigated through washing and drying cycles, and the results are shown in Figure 5. It is interesting to note that the lockstitch structure sensor gives readings that are systematically lower at first, though the nature of the signals remained unchanged. However, the readings become fully stable after 5 washing−drying cycles meaning the sensor works very well even after washing. The decrease of the reading could be due to the change of the deformable property of the cotton cloth after several washing−drying cycles. In addition, as shown in Figure S9, some peeling of the insulation layer (the cotton fiber) was evident after more than 20 washing−drying cycles. This aspect may be improved in a future study.

When a cell phone (idle and in operation, respectively) was placed beside the lockstitch structure sensor to look at possible effect of an electromagnetic perturbation, the results showed that there was little influence on sensing (see Figure S10).

In general, a creative design of the structure of capacitive pressure sensors has been demonstrated. This is the first time for the lockstitch structure to be used in making capacitive sensors. The unique characteristic of the lockstitch structure is its ability to make sensors integrated in any positions of the fabric through sewing, which solves the issues related to pressure sensing in irregular areas of the fabric. The small-sized lockstitch structure sensors are closely combined with the fabric. This will not affect the softness of the fabric and will show good sensing performance. Based on this fabrication strategy, more novel structures can be developed for making capacitive wearable sensors. The technique will resolve pressure sensing in irregular areas of a fabric on wearing objects. This may inspire further development of intelligent clothing.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssensors.0c00210.

Materials, instrumentation, preparation method, characterization of the core-spun yarn, and determination of bending behavior of textiles (PDF)

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Notes

The authors declare no competing financial interest.

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