Seamless integration of touch sensing smart textiles through computerized machine knitting

Md. Mohaddesh Hosen[1] (iD) **and Safi Ahmed[1]** (iD)

Abstract

The recent advancements in smart textiles have led to a surge in the use of textile-based sensors to detect various signals, including touch, pressure, body temperature, humidity, and so on. Due to their flexibility, bendability, and lightweight design, all of which make them perfect for a variety of flexible sensing systems. Herein, a capacitive touch sensor consisting of all textile components has been architected through computerized machine knitting technology. The prototype has been realized with the double knit intarsia knitting technique, which enables seamless integration of touch sensing textiles onto non-conductive base fabric during single knitting operations. This simple and easily embedded touch interface enables users to experience soft and ultraflexible electronic textiles with high responsive (response time ~80 ms) sensing capabilities. High reproducibility and repeatability were observed with the manufactured capacitive touch sensor, with negligible change in capacitance within 500 touched-untouched cycles. The sensor also demonstrates outstanding flexibility against various mechanical deformations, that is, twisting, grasping, folding, and pinching. As a proof of concept, a machine knitted touch keyboard, numpad, wristband, and soft switch have been demonstrated as capacitive touch sensing user interfaces for human-machine interaction.

Introduction

The ubiquity of textiles for conformal coverings next to the human skin over the millennia makes it a promising platform for embedding wearable sensors,[1–4] energy harvesting devices,[5–7] energy storage devices,[8–10] and antennae[11–13] into it. Combining wearable sensors with conventional garments has become very popular due to its ability to capture on-body signals such as touch stimuli,[14,15] body temperature,[16,17] heart rate,[18,19] pulse rate,[20–22] and respiration rate.[23,24] Generally, there are three types of electronic textile-based sensors, that is, piezoresistive,[25–27] capacitive,[28–30] and inductive.[31,32] Among these, capacitive

touch sensors have been a major developing area in the context of smart e-textiles. Usually, touch sensors are designed to transduce touch stimuli into a measurable electrical signal. Variations in capacitance can be detected by touch sensors.

[1]Department of Fabric Engineering, Faculty of Textile Engineering, Bangladesh University of Textiles, Dhaka, Bangladesh

Corresponding author:
Md. Mohaddesh Hosen, Department of Fabric Engineering, Faculty of Textile Engineering, Bangladesh University of Textiles, 92, Shahid Tajuddin Ahmed Sarani, Tejgaon I/A, Dhaka 1208, Bangladesh.
Email: mohaddesh@fe.butex.edu.bd

The development of smart sensors involves conventional rigid electronics as well as flexible film-based polymers. These sensors are fabricated by various techniques, including photolithography,[33] surface etching,[34] nanofibrous aerogels,[35] etc., which are very complex and expensive. Although these sensors show good palpability and sensing capability, they perform poorly in terms of wearability and comfort. However, problems regarding electronic waste and sustainability in sensor manufacturing are still an issue.

General requirements for developing smart e-textiles now include reduced wastage of functional components, integration of electronic parts at localized positions, and an easy and scalable fabrication process. To overcome these challenges, textile manufacturing can be a better choice. Textile-based sensors can be produced via knitting,[36–39] weaving,[40–44] embroidery,[45–47] and stitching[48] and they may require other post-processing techniques like coating,[49] screen printing[50] etc. From the beginning to the date of the e-textile research, sewing,[51,52] embroidery,[45] and snap buttons[53] to attach conductive materials into garments have been considered as popular sensor embellishment techniques, but the resultant sensing interfaces suppress comfortability and bendability. Besides, machine weaving inhibits the ability to embed conductive yarns at any desired location, resulting in an increase of electronic waste.

However, machine knitting offers superior benefits over these popular techniques. Computerized machine knitting offers new possibilities for the sustainable manufacturing of flexible, stretchable, and easily tunable textile sensors. Among various knitting processes, the intarsia technique in knitting provides the flexibility of knit-at-will, that is, placing the conductive yarns in any desired position. This facilitates the reduction of waste of electronic components fulfilling the requirement of sustainable manufacturing of electronic textiles. This technique also produces fabrics that are easily scalable, soft, lightweight, flexible, comfortable, and cost-effective. They have good mechanical strength to withstand repetitive wear without compromising their sensitivity over a long period of time.

In this era of ubiquitous computing and human-machine interaction, textile-based touch sensors can play a vital role. Its application prototypes have been demonstrated in previous studies.[40,41,46,54] Usually, capacitive touch sensors are of two types, that is, single-electrode-based self-capacitive touch sensors[55,56] and double-electrode-based mutual capacitive touch sensors.[48,57] A considerable amount of research has been explored on the fabrication of textile-based capacitive touch sensors. Abdullah al Rumon and Shahariar[48] developed a mutual capacitive touch sensor using off-the-shelf conductive thread and lockstitch sewing techniques. Sewing techniques are often lengthy, complex, and not easily scalable, which requires manual post-processing for sensor integration. In another work, a capacitive touch sensor was developed using the weaving technique, which is a three-layer woven fabric.[40] Here, sensing yarns are floated on the front and back sides of the fabric, which may be prone to snagging and induce discomfort for the wearer. Wu et al.[58] developed a capacitive sensor to detect human motion that uses woven nylon fabric as an electrode and ecoflex as a dielectric layer. Ghosh et al.[49] developed a reduced graphene oxide (rGO)-coated merino wool/nylon capacitive touch sensor to turn "on" and "off" a light bulb. The proposed method shows the change in capacitance from ~0.25 pF to ~0.55 pF when the sensor is touched. However, these proposed methods are hardly scalable and susceptible to stiffness, which hampers the flexibility of these sensors.

Here, we report machine knitted single electrode based capacitive touch sensors that incorporate commercial conductive yarn to achieve cost-effectiveness, allowing seamless integration into other non-conductive textile materials. The fabrication process involves embedding capacitive touch sensors directly into the fabric using the double knit intarsia technique through a computerized flatbed knitting machine. We prefer machine knitting over other fabric manufacturing techniques due to its unique features. With recent advances in state-of-the-art computerized design and fabrication technology, digital knitting machines offer knit-at-will fabrication opportunities through which we can architect soft, flexible touch sensing interfaces that are breathable and pleasant to touch. This feature allows us to construct any knitted textile with the accurate placement of any sensor anywhere in the clothing by precise control of the fabric's geometrical parameters. By utilizing this advanced machine knitting technique, capacitive touch sensors can be manufactured with assured reproducibility without hampering their performance. Electromechanical characterization of the developed touch sensors demonstrates good mechanical stability under repeated deformation, good cyclic performance, ultra-flexibility, and high response and recovery times. We successfully tested our sensor's capabilities by using it as a flexible keyboard, numpad, wristband, and soft switch for a servo motor, thereby ensuring its potential use in the field of human-machine interaction.

Materials and methods

Materials

To fabricate the self-capacitive touch sensor using the machine knitting technique, conductive and non-conductive yarns are required. The non-conductive acrylic base yarn (200 dtex $\times$ 2) was purchased from a local spinning industry. Polyester/stainless steel (60/40) conductive yarn (400 dtex $\times$ 3) with a linear resistance of 6 Ω/cm was purchased from Bekaert, Belgium. The physical properties of both conductive and non-conductive yarns are given in Table 1. The sensor was designed in the KnitPaint module of SDS One Apex 3 software and fabricated using an

Table 1. Physical properties of the yarns used for knitting the sensors.

Yarn type	Yarn composition	Linear density (dtex)	Thickness of yarn (µm)	Stress at yield (N)	Stress at break (N)	Strain (%)	Resistance (Ω/cm)
Conductive	Polyester/Stainless steel (60/40)	400 dtex × 3	409	2.407	2.407	7.4	6
Non-conductive	100% Acrylic	200 dtex × 2	234	1.883	1.883	13.2	-

SSR112_14G computerized flat knitting machine (Shima Seiki, Japan).

Knitting capacitive sensors

The sensor consists of three parts: hem, non-conductive base part, and conductive sensor part (Figure 1(a)). Carrier 5 was used for hem knitting, which is a basic 1×1 rib structure, and the base fabric is an all-needle double jersey rib structure knitted with carrier 2 as shown in Figure 1(b). Two conductive yarns were employed to knit the sensors utilized by carriers 3 and 4. An advanced knitting technique, that is, Intarsia, was used to integrate off-the-shelf commercial conductive yarn into non-conductive base fabric. In this technique, a single course was knitted, either with two carriers (carrier 2 and carrier 4) or with three carriers, one for the non-conductive base yarn (carrier 2) and two for conductive functional yarns (carriers 3 and 4), as depicted in Figure 1(b) and (c), respectively.

To fabricate sensors with different sizes, shapes, and forms, such as alphabets, numbers, and rectangles, carrier interference with needles was a common issue while producing this sensor. So, precise carrier positioning, needle selection, and carrier traversing were several challenges while knitting the sensor with intarsia, which were adjusted by giving accurate instructions while designing the sensor in the KnitPaint module of Apex 3 software as shown in Figure 2(a). Carrier-to-carrier distance (Supporting Information, Figure S1) was set in the knitting machine to an optimum value to avoid disruptions during the knitting. As in intarsia, each of the sensors was knitted separately, and the yarn was not carried across the back of the work, which assures a flexible structure with no yarn floating as shown in Figure 2(c). Here, the self-capacitive touch sensing interface was devised on a Shima Seiki SSR 112_14G digital flatbed knitting machine, as shown in Figure 2(b). The run-in tension of the conductive yarn was maintained at 11 cN during the knitting operation, and the knitting speed was 0.70 m/s. This knitting machine is equipped with nine yarn carriers, of which four were employed to manufacture the desired sample. Two carriers were used to exclusively feed the conductive yarn, whereas the other two were responsible for base fabric and waste knitting. The knitting was performed in both the front and back beds, as the sensor and base structures were of double knit.

The fabricated sensor exhibited a course density and wale density of 20 courses per inch and 15 wales per inch,

respectively. Keeping constant run-in tension of the conductive yarn during knitting to maintain uniform stitch length was an important issue. In order to achieve this, the yarn tension was set accurately, and a DSCS (Digital Stitch Control System) was used, which is located on the side of the flatbed knitting machine. To eliminate the possibility of fabric, pile up in between the two needle beds, an optimum takedown value (Supporting Information, Figure S3) was set.

Figure 3 illustrates the overall knitting programing sequence of the capacitive touch sensor. Figure 3(a) shows the color code instructions for developing the sensor in the KnitPaint module. Here, color code 2 (green) refers to non-conductive base yarn and color code 3 (yellow) denotes conductive yarns. Figure 3(b) and (c) shows the needle bed simulation view and the simulated sample in the software, respectively, and Figure 3(d) shows the actual developed sample.

Self-capacitive touch sensing mechanism

The working mechanism of the fabricated single-electrode-based self-capacitive touch sensor is based on the electrical charge-discharge principle when it is touched and when it is not. The detailed working mechanism of the sensing unit is described in Figure 4. At its initial state, as depicted in Figure 4(a), the sensor has a capacitance of C_a when it is not subjected to touch by any means. Here, the capacitance is measured by totally discharging it to the ground after charging it periodically. Therefore, the capacitance of the sensor is calculated as below:

$$C = \frac{Q}{V} = \frac{I \times T}{V} \qquad (1)$$

When a current is applied to the sensor for a certain amount of time, the voltage (V) is measured, and the capacitance (C_a) is calculated according to equation (1).

When the sensor is touched by a human finger or other ferromagnetic objects, a parallel capacitor connection is established between the sensor (C_a) and the human finger (C_b), as shown in Figure 4(b). As a result, more charge is induced on the sensor surface, thus increasing the capacitance. So, the resultant capacitance (C_r) will be as follows:

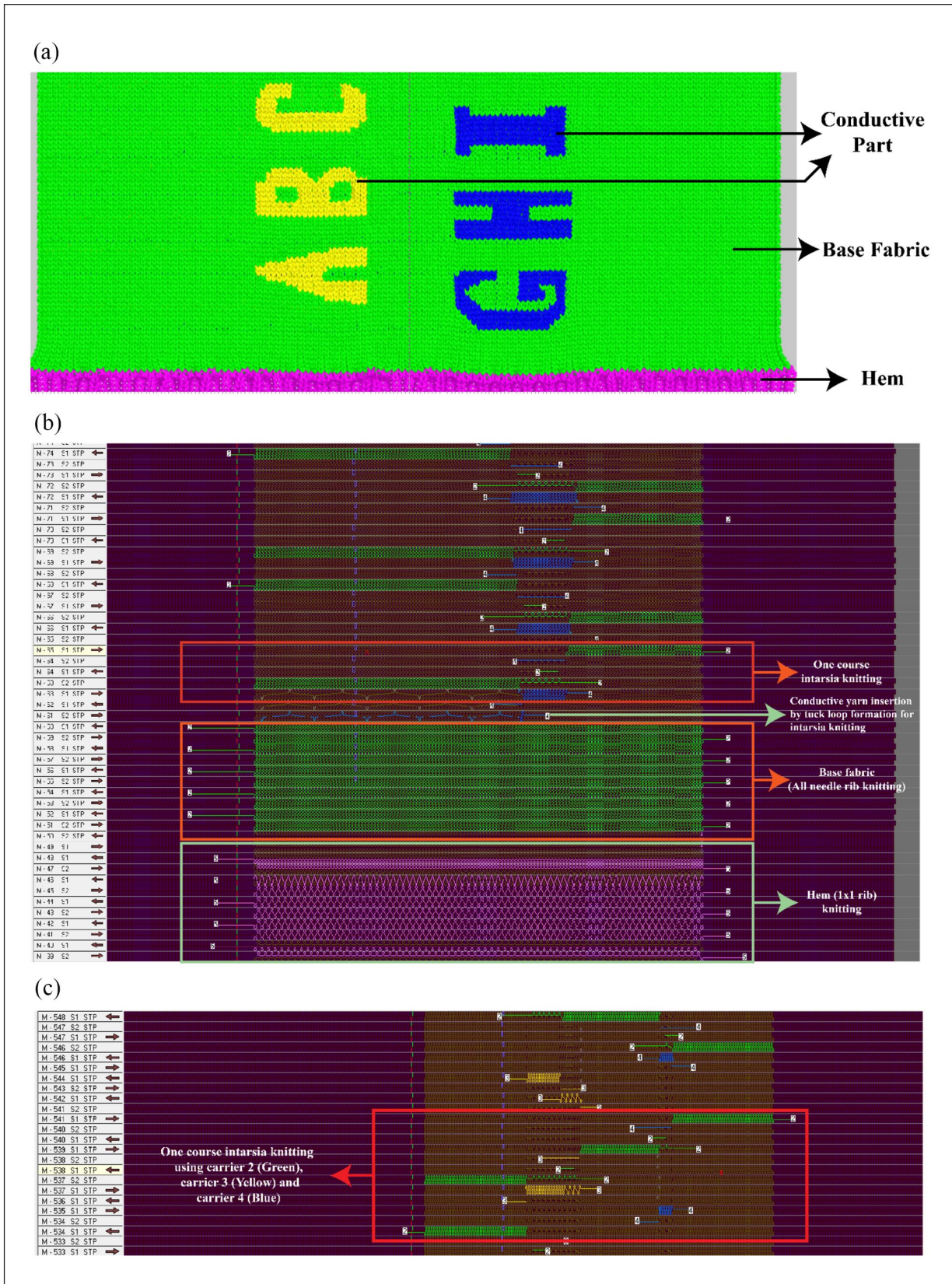$$C_r = C_a + C_b \qquad (2)$$

Figure 1. Simulated view and needle notation diagram of the developed sensor designed in Shima Seiki Apex 3 software. (a) Simulated view of the sensor with hem, base fabric, and conductive part, (b) looping diagram of hem, base fabric, and conductive part, (c) side-by-side conductive part integration onto base fabric using the intarsia technique.
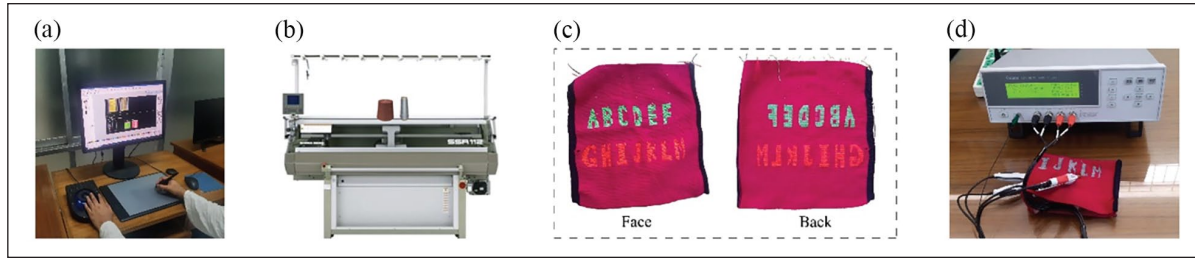
Figure 2. Schematic of capacitive touch sensor fabrication and characterization: (a) knitting file processing, (b) knitting of the sensor, (c) fabricated sample, and (d) sensor characterization.
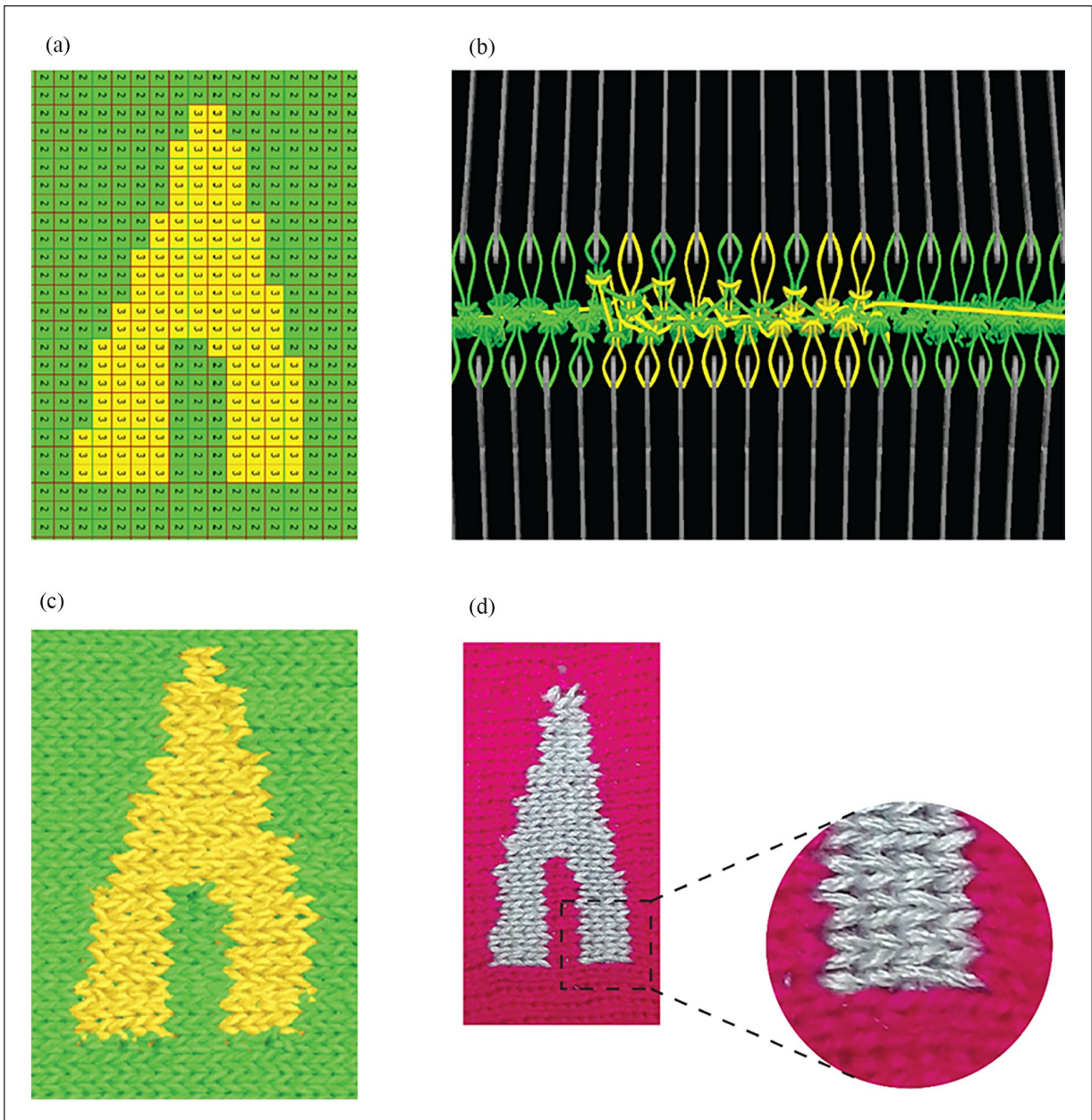

Figure 3. Knitting programing and simulation: (a) color code instruction for the KnitPaint module, (b) virtual knitting simulation, (c) simulated loop view, (d) fabricated knitted sample (inset: close-up view of interconnections between conductive and non-conductive yarn).
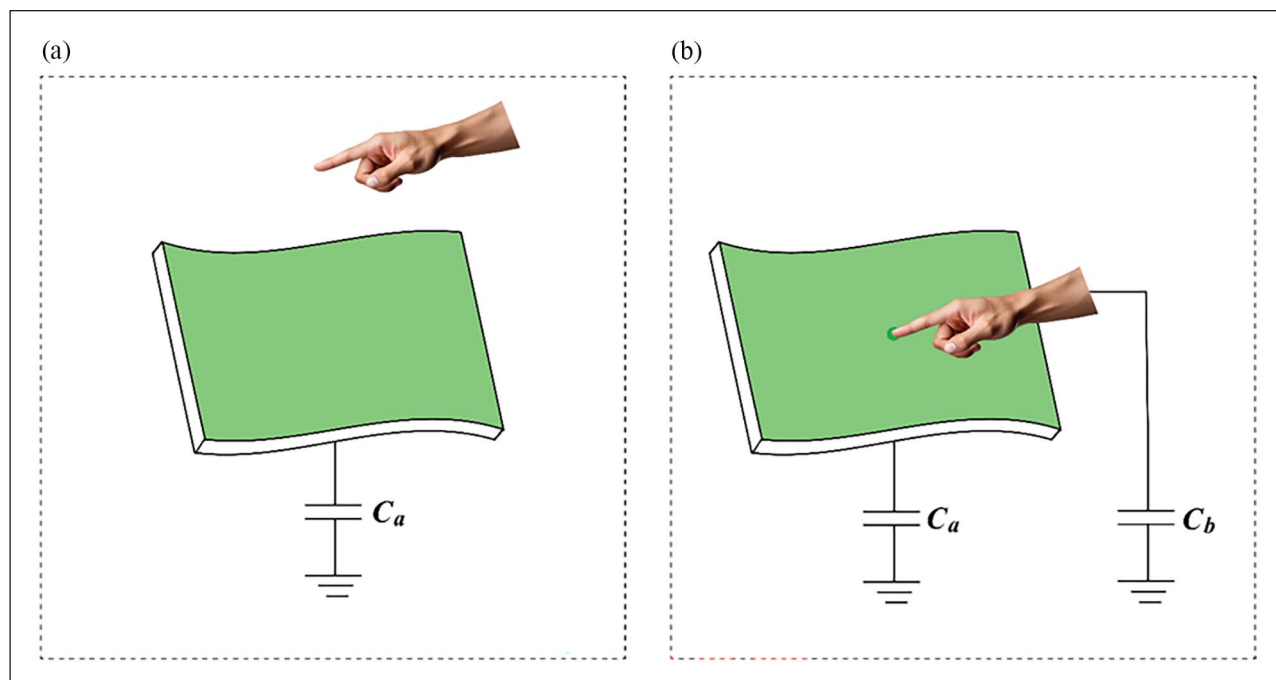
Figure 4. Sensing mechanism of the self-capacitive touch sensor, which detects capacitance change between the sensor and a human finger when untouched (a) and touched (b).

Sensor characterizations

Electromechanical characterization of the sensor: The capacitance of the fabricated sensor was measured at room temperature by an LCR meter (Chroma 11021-L, Taiwan), as shown in Figure 2(d). The detailed touch-untouch capacitance value is given in Figure S4, Supporting Information. Cyclic test of the sensor was carried out using a microcontroller (Arduino Leonardo ATmega32U4, Microchip Technology Inc., USA) and a capacitive touch sensor (MPR121, NXP Semiconductors, Netherlands). Response time of the sensor means the time taken to shift the baseline after it was touched. It was determined by touching the sensor with a frequency of 1 Hz.

Washability test: The washability test of the sample was done according to the BS EN ISO 105-C10 test method. The sample was allowed to undergo mechanical agitation in a mechanical laundering device with 10 steel balls inside the device. A commercially available washing powder was used for the test. After each test, the sample was dried in the open air. Twenty washing cycles were observed in this process.

Flexibility test: The flexibility of the developed sensor was tested using a cantilever test instrument. For the test procedure, ASTM standard D 1388-07 was followed. The testing procedure for the flexibility test is described in Note S5, Table S1, and Figure S5 of the Supporting Information.

Abrasion resistance test: A 2000-cycle abrasion resistance test was performed by a Martindale abrasion tester machine. A sample of 38 mm in diameter was used for this test. A weight was used to apply 9 kPa pressure to the sample. The ISO 12947 standard testing method was followed for the test. Optical images of the sample before and after 2000-cycle abrasion tests are given in Figure S6, Supporting Information.

Results and discussion

Electromechanical performance of sensor

Among various fabric structures, double knit fabric was selected due to its desired wearability and mechanical performance. Good washability, resistance to mechanical stresses like abrasion and stretching, and high flexibility are some important parameters for wearables. The sensor shows good stability under repeated washing and mechanical stresses, that is, twisting and abrasion. Figure 5(a) shows little change in the capacitance of the sensor, that is, 2.86%, 1.62%, and 5.42% after repeated washing, twisting, and abrasion, respectively. Figure 5(b) shows the changes in capacitance while touching at different frequencies. It is observed that the sensor experienced minimal changes in capacitance after it was touched and untouched on frequencies of 0.7, 1, 2, and 4 Hz, respectively. To evaluate the different electromechanical performances of the sensor, identical structural parameters, that is, stitch length, stitch density, and conductive yarn type, were maintained while knitting the samples.
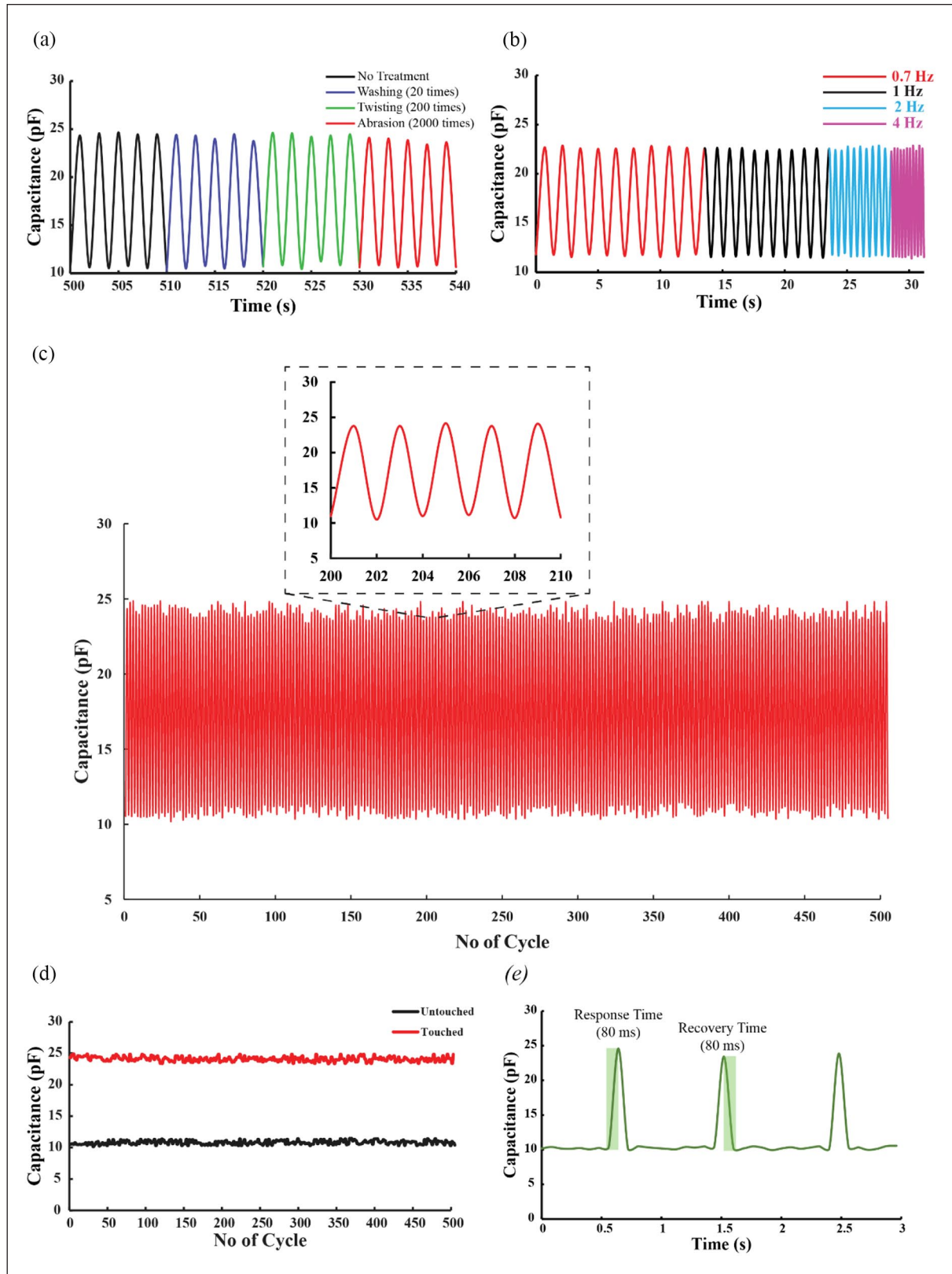
Figure 5. (a) The capacitance of the sensor under repeated touch-untouch in various states, that is, original, washing, twisting, and abrasion; (b) Changes in capacitance in response to various tapping frequencies, that is, 0.7–4 Hz; (c) Cyclic test results for up to 500 touch-untouch cycles. (inset: the output of the sensor between 200 and 210 cycles); (d) Capacitance value (pF) when the sensor is touched and untouched during the cyclic test; (e) The response and recovery time of the sensor.

Figure 6. Different mechanical deformations were applied to the developed sensor to assure its ultra-flexibility and stable electrical characteristics: (a) twist, (b) multi-fold, (c) grasp, (d) two-finger pinch, (e) two-fold, and (f) flat state.

In addition, the developed sensor shows good cyclic stability under repeated touch-untouch. The cyclic stability test was done up to 500 cycles with a frequency of 0.7 Hz, as shown in Figure 5(c). Figure 5(c)'s inset shows a zoomed-in version of a portion of the cyclic test. This shows minimal changes in capacitance, confirming the developed sensor's practical applicability and robustness. During the cyclic tests, capacitance value of each touch and untouch is depicted in Figure 5(d) which shows that the mean capacitance during touching and untouching is 24.09 pF and 10.81 pF, respectively. The coefficient of variation of capacitance during touching is 1.25% and 3.47% when it remains untouched. This low coefficient of variation also demonstrates high stability of the sensor. To evaluate the practical use of the sensor, the response and recovery time of the sensor were measured by maintaining a touching frequency of 0.7 Hz, as shown in Figure 5(e). We observed that our developed sensor has a response and recovery time of ~80 ms. All of the electromechanical performances described in Figure 5 ensure that this sensor can be used in real-world applications.

Mechanical stability of sensor

The developed sensor shows good stability against different mechanical deformations, that is, twisting, folding, grasping, and pinching, as depicted in Figure 6(a) to (e). Even after the sensor underwent various mechanical deformations, it came back to its original state without sacrificing any notable electrical changes, as shown in Figure 6(f). The developed sensor shows good flexural properties with an average bending length of 1.74 cm, which assures the sensor's ultra-flexibility.

Versatile touch sensing capability

As shown in Figure 7, the applicability of the sensor was tested by touching it with four different materials, that is, human finger, conductive fabric, metal nail, and non-conductive fabric. The sensor was independent of touch frequency or touch time throughout the test. It is evident that the sensor can detect any conductive material, including human fingers (Supporting Information, Figure S4). However, the non-conductive fabric was unable to establish a connection with the ground, so no parallel
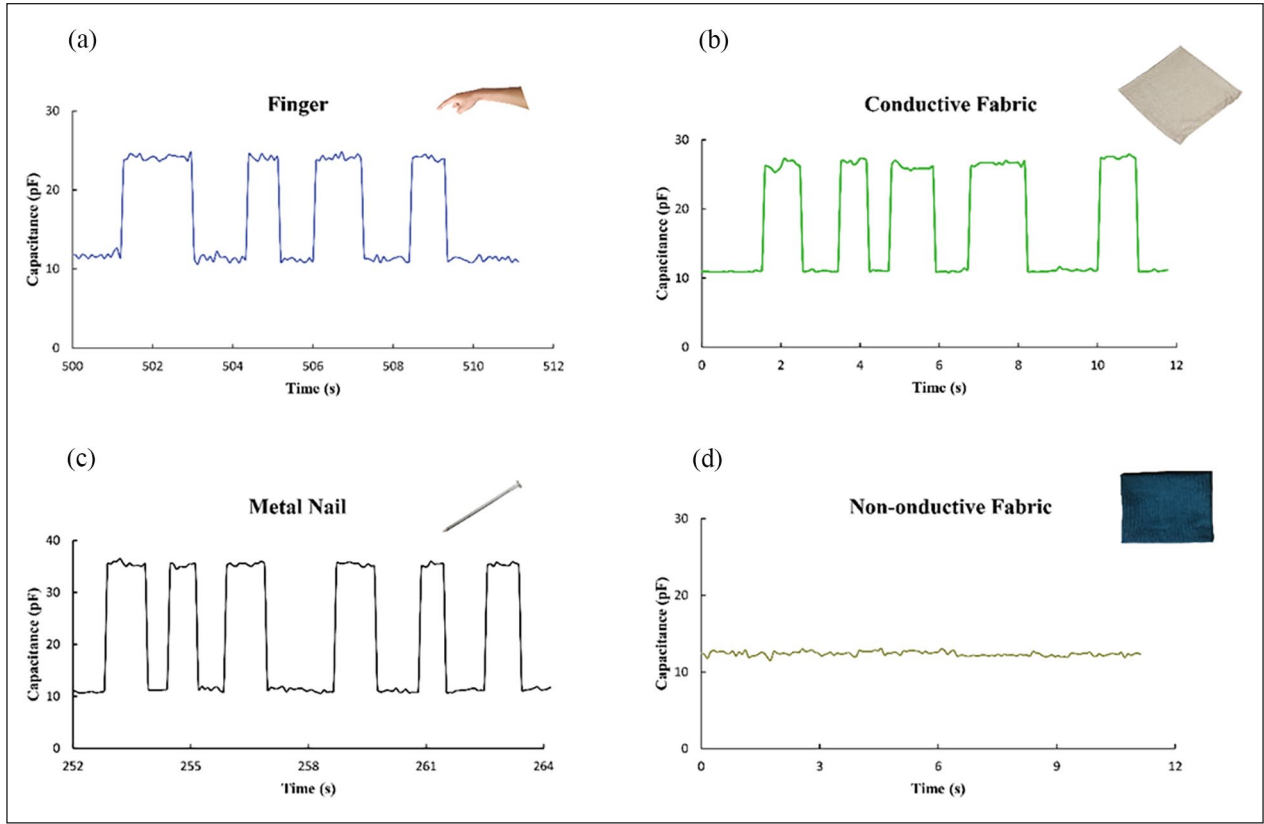
Figure 7. Sensor performance evaluation by tapping with (a) human finger, (b) conductive fabric, (c) metal nail, and (d) non-conductive fabric.

connection was made with the sensor, as shown in Figure 4. As a result, no contact was detected. This confirms our sensor's suitability in the realm of human-machine interaction.

Comparative study

This work emphasizes the design and development of knitted capacitive touch sensors using the intarsia knitting technique. This technique offers minimal wastage and rapid prototyping compared to other fabrication techniques, including weaving, embroidery, sewing, printing, etc. Although various capacitive touch sensors using a single-electrode capacitive technique have been reported so far, the durability and washability of these textile-based touch sensors have hardly been discussed. Sensor performance in terms of change in capacitance due to touch is also an issue that has been overlooked in most literature. Table 2 below shows the comparative analysis among various capacitive touch sensors and their suitability in daily use. While direct comparison among various sensors is often difficult due to the versatility of different works, a few of the attributes have been discussed below.

Application demonstration of the developed sensor

The rapid response time, ultra-flexibility, and good cyclic stability combined with the controllable geometrical area widen the applicability of the machine knitted touch sensor. As our developed touch sensor demonstrates these characteristics, we integrated touch sensors into fabric in various sizes, shapes, and forms, that is, alphabet, number, rectangle, or square, to explore the versatility, applicability, and suitability of our developed sensor in human-machine interaction applications. In order to detect active touch, the developed sensor is independent of the human finger dimension. It is capable of detecting senses in any area of the body.

Figure 8(a) demonstrates the circuit interconnections between the touch sensors and the computer. Here, the sensor is connected to the ADC module via wired interconnection, and the ADC module is connected to the microcontroller unit by an I^2C bus connection. The microcontroller is then connected to the computer via a USB cable. For these demonstrations, an ATmega32U4-based microcontroller has been used because it can transmit

Table 2. Comparative study of various capacitive touch sensors.

| Sl no.	Fabrication Technique	Sensing Principle	Function	Materials	ΔC due to Touch	Cyclic test	Wash Cycle	Application	Ref
1.	Knitting	Single electrode capacitive sensing	Touch sensing	Polyester/stainless steel conductive yarn	~14 pF	500	20	Touch sensing for human-machine interaction	[This work]
2.	Knitting (Lace)	Single electrode Capacitive sensor	Sensor-actuator (touch-heating)	20% stainless steel conductive yarn	-	-	-	Heating textiles	Kuusk et al.[59]
3.	Knitting, Weaving, printing, embroidery	Capacitive	Touch sensing	Silver coated conductive threads, Copper beads	-	-	-	Multi-sensory tactile stimulation	Tan et al.[60]
4.	Weaving	Single electrode capacitive sensing	Touch sensing	PEDOT: PSS	2.44pF	-	-	-	Bahadir et al.[52]
5.	Weaving	Single electrode capacitive sensing	Touch sensing	Copper core-silk braided yarn	-	-	Not specified	Interactive textiles and internet of things	Wicaksono and Paradiso[38]
6.	Weaving	Single electrode capacitive sensing	Touch sensing	Silve coated nylon yarn	-	-	10	Illumination by luminescene fabric	Tan et al.[61]
7.	Embroidery	Single electrode capacitive sensing	Touch sensing	Polyester/stainless steel conductive yarn	-	-	Not specified	Touch based music controller	Post et al.[62]
8.	Embroidery	Single electrode capacitive sensing	Sliding and touch sensing	Silver plated nylon yarn	-	-	-	Touch and slide gesture recognition on textile surface	Al-Huda Hamdan et al.[63]
9.	Embroidery	Single electrode capacitive sensing	Touch sensing	Silver coated nylon yarn	-	-	10	Touch sensitive illuminated garments	Bai et al.[64]
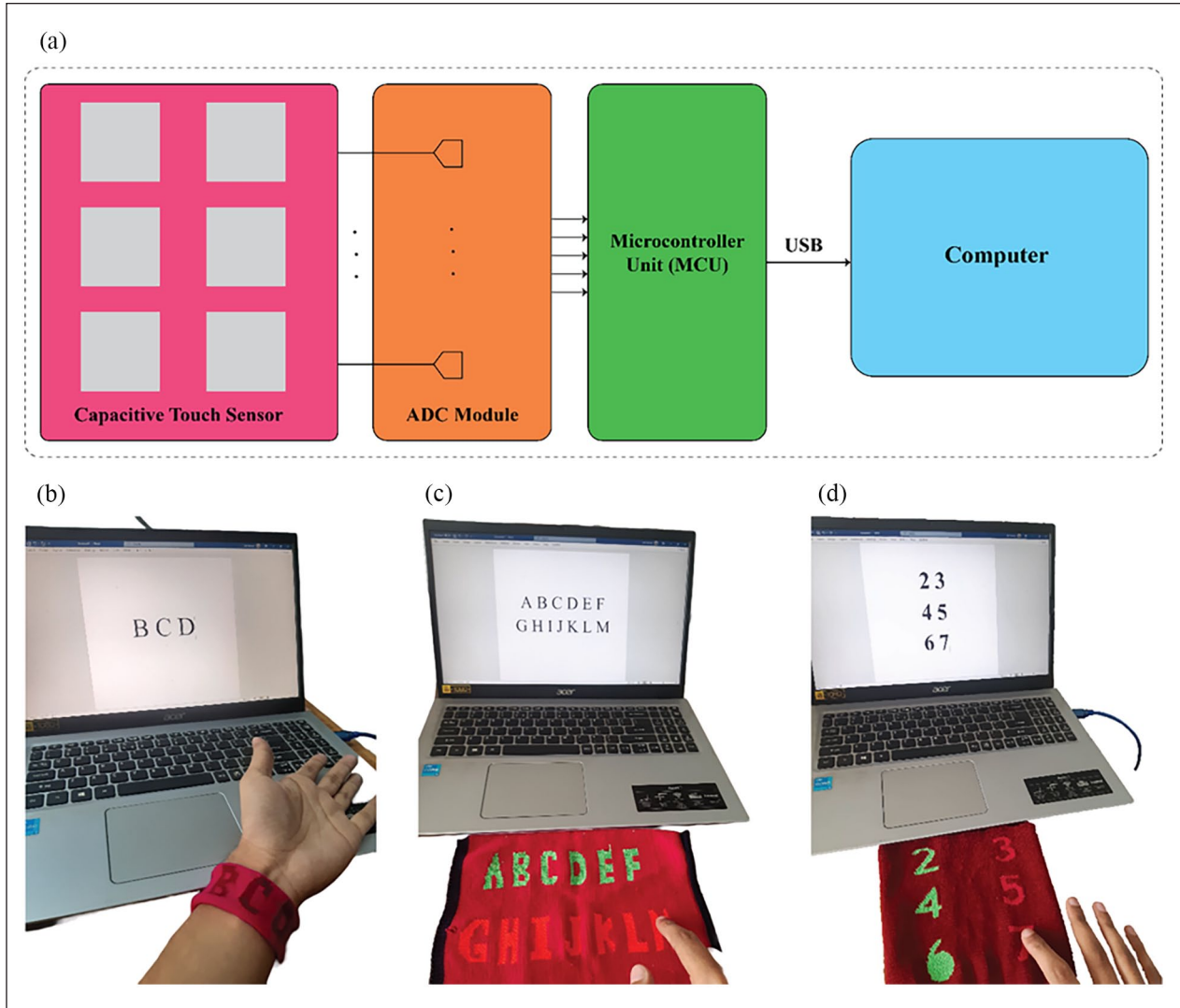
Figure 8. Real-time application demonstration of capacitive touch sensing smart textiles. (a) Schematic block diagram for acquiring touch signals for human-machine interaction. Working prototype of the developed sensor as machine knitted (b) wristband, (c) keyboard, and (d) numpad.

keystrokes to a connected computer via the microcontroller's native USB connector. A detailed circuit diagram of the developed sensor is given in Supporting Information, Figure S7. Figure 8(b) shows the application of the developed sensor as a flexible keyboard (Movie S2, Supplemental Video). The keyboard detects each touch on the machine knitted alphabet and displays it on the computer screen. This application assures our sensor's suitability as a highly flexible keyboard that can be used anywhere. The flexible capacitive sensor can be employed as a numpad and wristband, as shown in Figure 8(b) to (d). We placed the developed sensor on the hand as a smart wristband and a numpad that can be used anywhere without any hassle. Additionally, this hand wristband can be used as an interactive learning tool for kids and others.

We further developed our sensor as a soft switch to demonstrate the use of this sensor in human-machine interaction. The developed sensor can be used as a flexible soft switch. As shown in Figure 9, a servo motor is controlled by the developed soft switch. When the sensor is touched, the rotor of the servo motor rotates from 0° to 180° (Figure 9(a) and (b)). When the sensor is touched again, the rotor returns from 180° to 0° (Figure 9(c) and (d); Movie S3, Supplemental Video). That means each of the touches is detected as an individual sense. This confirms the use of this sensor as a human-machine interaction tool that can be used for various robotics applications.

Conclusion

We report an easily customizable and fast manufacturing of single-electrode-based capacitive touch sensing textiles for smart textile applications. Our approach utilizes computerized flatbed knitting technology for easy integration of off-the-shelf conductive yarn onto
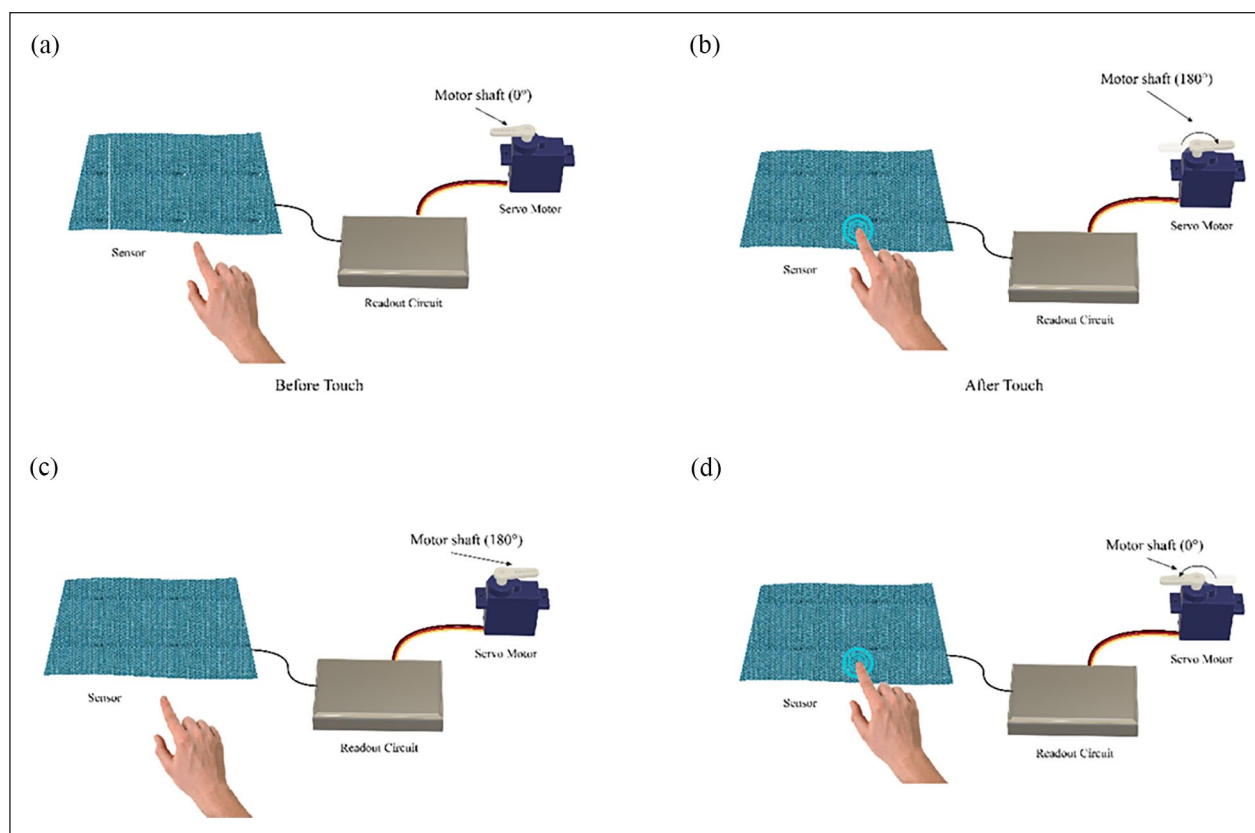
Figure 9. Application prototype of the developed sensor as a soft switch. The Motor shaft rotates from 0° (a) to 180° (b) and returns to its previous position from 180° (c) to 0° (d) in response to touch.

non-conductive fabric to produce touch sensors. The fabricated sensors are washable, ultra-flexible, and bendable, demonstrating excellent cyclic stability, high responsiveness, mechanical stability, and broader touch sensing capability. We reveal the potentiality of the developed sensor as a proof of concept by simply embedding touch sensors in various forms, including an array of alphabets as a knitted keyboard and wristband, numbers as a numpad, and rectangular interfaces as a soft touch switch to control programmable servo motors. This seamless integration of touch sensors onto base fabric ensures rapid and robust functional integration, which accelerates the commercialization of touch sensors.

ORCID iDs

Md. Mohaddesh Hosen https://orcid.org/0009-0006-0409-4421
Safi Ahmed https://orcid.org/0009-0001-7016-505X

Statements and Declarations

Conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Supplemental material

Supplemental material for this article is available online.

References

1. Schneegass S and Voit A. GestureSleeve: Using touch sensitive fabrics for gestural input on the forearm for controlling smartwatches. In: *International symposium on wearable computers, digest of papers*, 2016, pp.108–115. New York: IEEE Computer Society.
2. Parzer P, Sharma A, Vogl A, et al. SmartSleeve: realtime sensing of surface and deformation gestures on flexible, interactive textiles, using a hybrid gesture detection pipeline. In: *UIST 2017 - Proceedings of the 30th annual ACM symposium on user interface software and technology*, 2017, pp.565–577. Association for Computing Machinery, Inc.
3. Zhang Q, Wang YL, Xia Y, et al. Textile-only capacitive sensors for facile fabric integration without compromise of wearability. *Adv Mater Technol* 2019; 4(10). DOI: 10.1002/admt.201900485
4. Vu CC and Kim J. Highly elastic capacitive pressure sensor based on smart textiles for full-range human motion monitoring. *Sens Actuators A Phys* 2020; 314: 112029.

5. Wang J, He J, Ma L, et al. A humidity-resistant, stretchable and wearable textile-based triboelectric nanogenerator for mechanical energy harvesting and multifunctional self-powered haptic sensing. *Chem Eng J* 2021; 423: 130200.

6. Mokhtari F, Spinks GM, Fay C, et al. Wearable electronic textiles from nanostructured piezoelectric fibers. *Adv Mater Technol* 2020; 5(4): 1900900. DOI: 10.1002/admt.201900900

7. Yin L, Kim KN, Lv J, et al. A self-sustainable wearable multi-modular E-textile bioenergy microgrid system. *Nat Commun* 2021; 12(1): 1542.

8. Islam MR, Afroj S and Karim N. Scalable production of 2D material heterostructure textiles for high-performance wearable supercapacitors. *ACS Nano* 2023; 17(18): 18481–18493.

9. Sun T, Shen L, Jiang Y, et al. Wearable textile supercapacitors for self-powered enzyme-free smartsensors. *ACS Appl Mater Interfaces* 2020; 12(19): 21779–21787.

10. Khan A, Grabher G and Hossain G. Smart-textile supercapacitor for wearable energy storage system. *J Energy Storage* 2023; 73: 108963.

11. El Gharbi M, Fernández-García R and Gil I. Embroidered wearable antenna-based sensor for real-time breath monitoring. *Measurement* 2022; 195: 111080.

12. Kazemi KK, Zarifi T, Mohseni M, et al. Smart superhydrophobic textiles utilizing a long-range antenna sensor for hazardous aqueous droplet detection plus prevention. *ACS Appl Mater Interfaces* 2021; 13(29): 34877–34888.

13. Garnier B, Mariage P, Rault F, et al. Textile NFC antenna for power and data transmission across clothes. *Smart Mater Struct* 2020; 29(8): 085017.

14. Ku PS, Shao Q, Wu TY, et al. ThreadSense: Locating Touch on an Extremely Thin Interactive Thread. In: *Conference on human factors in computing systems - proceedings, 2020*, 2024, pp.1–17. Association for Computing Machinery. DOI: 10.1145/3313831.3376779.

15. You X, He J, Nan N, et al. Stretchable capacitive fabric electronic skin woven by electrospun nanofiber coated yarns for detecting tactile and multimodal mechanical stimuli. *J Mater Chem C* 2018; 6(47): 12981–12991.

16. Jiang Y, Pan K, Leng T, et al. Smart textile integrated wireless powered near field communication body temperature and sweat sensing system. *IEEE J Electromagn RF Microw Med Biol* 2020; 4(3): 164–170.

17. Jung S, Ji T and Varadan VK. Point-of-care temperature and respiration monitoring sensors for smart fabric applications. *Smart Mater Struct* 2006; 15(6): 1872–1876.

18. Zhao J, Deng J, Liang W, et al. Water-retentive, 3D knitted textile electrode for long-term and motion state bioelectrical signal acquisition. *Compos Sci Technol* 2022; 227: 109606.

19. Karim N, Afroj S, Malandraki A, et al. All inkjet-printed graphene-based conductive patterns for wearable e-textile applications. *J Mater Chem C* 2017; 5(44): 11640–11648.

20. Fan W, Li C, Li W, et al. 3D waterproof mxene-based textile electronics for physiology and motion signals monitoring. *Adv Mater Interfaces* 2022; 9(14): 2102553. DOI: 10.1002/admi.202102553

21. Zhang X, Tang S, Ma R, et al. High-performance multi-modal smart textile for artificial sensation and health monitoring. *Nano Energy* 2022; 103: 107778.

22. Fan W, He Q, Meng K, et al. Machine-knitted washable sensor array textile for precise epidermal physiological signal monitoring. *Science Advances* 2020; 6(11). DOI: 10.1126/sciadv.aay2840

23. Si S, Sun C, Qiu J, et al. Knitting integral conformal all-textile strain sensor with commercial apparel characteristics for smart textiles. *Appl Mater Today* 2022; 27: 101508.

24. Feng Z, He Q, Qiu J, et al. Iontronic textile-based capacitive pressure sensor for unconstrained respiration and heartbeat monitoring. *Adv Mater Technol* 2023; 8(22): 2300949. DOI: 10.1002/admt.202300949

25. Chen J, Zhang J, Hu J, et al. Ultrafast-response/recovery flexible piezoresistive sensors with DNA-like double helix yarns for epidermal pulse monitoring. *Adv Mater* 2022; 34(2): 2104313. DOI: 10.1002/adma.202104313

26. Khan A, Rashid M and Hossain G. Industrially scalable piezoresistive smart-textile sensor for flexible electronics application. *ACS Sens* 2023; 8(12): 4801–4809.

27. Mira RA, Haberfellner A, Haller M, et al. Loopsense: low-scale, unobtrusive, and minimally invasive knitted force sensors for multi-modal input, enabled by selective loop-meshing. In: *Proceedings of the CHI conference on human factors in computing systems*, 2024, pp.1–17. Association for Computing Machinery (ACM).

28. Martínez-Estrada M, Ventura H, Gil I, et al. A full textile capacitive woven sensor. *Adv Mater Technol* 2023; 8(1): 2200284. DOI: 10.1002/admt.202200284

29. Yilmaz AF, Ahmed IAK, Gumus C, et al. Highly stretchable textile knitted interdigital sensor for wearable technology applications. *Adv Sens Res* 2024; 3(2): 2300121 DOI: 10.1002/adsr.202300121

30. Zhao B, Dong Z and Cong H. A wearable and fully-textile capacitive sensor based on flat-knitted spacing fabric for human motions detection. *Sens Actuators A Phys* 2022; 340: 113558.

31. Yang W, Lin S, Gong W, et al. Single body-coupled fiber enables chipless textile electronics. *Science* 1979; 384(6691): 74–81.

32. Tavassolian M, Cuthbert TJ, Napier C, et al. Textile-based inductive soft strain sensors for fast frequency movement and their application in wearable devices measuring multi-axial hip joint angles during running. *Adv Intell Syst* 2020; 2(4): 1900165. DOI: 10.1002/aisy.201900165

33. Si Y, Wang X, Yan C, et al. Ultralight biomass-derived carbonaceous nanofibrous aerogels with superelasticity and high pressure-sensitivity. *Adv Mater* 2016; 28(43): 9512–9518.

34. Shuai X, Zhu P, Zeng W, et al. Highly sensitive flexible pressure sensor based on silver nanowires-embedded polydimethylsiloxane electrode with microarray structure. *ACS Appl Mater Interfaces* 2017; 9(31): 26314–26324.

35. Pang C, Lee GY, Kim TI, et al. A flexible and highly sensitive strain-gauge sensor using reversible interlocking of nanofibres. *Nat Mater* 2012; 11(9): 795–801.

36. McDonald DQ, Vallett R, Solovey E, et al. Knitted sensors: designs and novel approaches for real-time, real-world sensing. *Proc ACM Interact Mob Wearable Ubiquitous Technol* 2020; 4(4): 1–25. DOI: 10.1145/3432201

37. McDonald DQ, Mahajan S, Vallett R, et al. Interaction with touch-sensitive knitted fabrics: user perceptions and

everyday use experiments. In: *Conference on human factors in computing systems - proceedings, 2022*. Association for Computing Machinery. DOI: 10.1145/3491102.3502077.

38. Wicaksono I and Paradiso JA. KnittedKeyboard: digital knitting of electronic textile musical controllers. In: *Proceedings of the international conference on new interfaces for musical expression*. 2020, pp.323–326.

39. Vallett R, McDonald DQ, Dion G, et al. Toward accurate sensing with knitted fabric: applications and technical considerations. *Proc ACM Hum Comput Interact* 2020; 4: 1–26.

40. Wu T, Fukuhara S, Gillian N, et al. ZebraSense: a double-sided textile touch sensor for smart clothing. In: *UIST 2020 - Proceedings of the 33rd annual ACM symposium on user interface software and technology*, 2020, pp.662–674. Association for Computing Machinery, Inc.

41. Poupyrev I, Gong NW, Fukuhara S, et al. Project Jacquard: interactive digital textiles at scale. In: *Conference on human factors in computing systems - proceedings*, 2016, pp.4216–4227. Association for Computing Machinery.

42. Sun R, Onose R, Dunne M, et al. Weaving a second skin: Exploring opportunities for crafting on-skin interfaces through weaving. In: *DIS 2020 - Proceedings of the 2020 ACM designing interactive systems conference*, 2020, pp.365–377. Association for Computing Machinery, Inc.

43. Egeli D, Seckin M, Seckin AC, et al. Woven fabric produced from coaxial yarn for touch sensing and optimization. *IEEE Sens J* 2022; 22(6): 5969–5977.

44. Agcayazi T, McKnight M, Kausche H, et al. A finger touch force detection method for textile based capacitive tactile sensor arrays. *Proc IEEE Sens*. Epub ahead of print 5 January 2016. DOI: 10.1109/ICSENS.2016.7808528

45. Hamdan NAH, Voelker S and Borchers J. Sketch&Stitch: interactive embroidery for e-textiles. In: *Conference on human factors in computing systems - proceedings*, 2018. Association for Computing Machinery. DOI: 10.1145/3173574.3173656.

46. Luo Y, Liu C, Lee YJ, et al. Adaptive tactile interaction transfer via digitally embroidered smart gloves. *Nat Commun* 2024; 15(1): 868.

47. Hamdan NAH, Blum JR, Heller F, et al. Grabbing at an angle: menu selection for fabric interfaces. In: *International symposium on wearable computers, digest of papers*, 2016, pp.1–7. IEEE Computer Society.

48. Abdullah al, Rumon M and Shahariar H. Fabrication of interdigitated capacitor on fabric as tactile sensor. *Sens Int* 2021; 2: 100086.

49. Ghosh S, Nitin B, Remanan S, et al. A multifunctional smart textile derived from merino wool/nylon polymer nanocomposites as next generation microwave absorber and soft touch sensor. *ACS Appl Mater Interfaces* 2020; 12(15): 17988–18001.

50. Chen Y, Deng Z, Ouyang R, et al. 3D printed stretchable smart fibers and textiles for self-powered e-skin. *Nano Energy* 2021; 84: 105866.

51. Chen W, Dols S, Oetomo SB, et al. Monitoring body temperature of newborn infants at neonatal intensive care units using wearable sensors. In: *Proceedings of the 5th international ICST conference on body area networks, BodyNets* 2010, 2011, pp.188–194.

52. Bahadir SK, Koncar V and Kalaoglu F. Smart shirt for obstacle avoidance for visually impaired persons. In: *Smart textiles and their applications*. Elsevier Inc, 2016, pp.35–70. DOI: 10.1016/b978-0-08-100574-3.00003-5

53. Dementyev A, Gálvez TV and Olwal A. SensorSnaps: Integrating wireless sensor nodes into fabric snap fasteners for textile interfaces. In: *UIST 2019 - Proceedings of the 32nd annual ACM symposium on user interface software and technology*, 2019, pp.17–28. Association for Computing Machinery, Inc.

54. Zhu J, Winagle L and Kao H-L. EcoThreads: prototyping biodegradable e-textiles through thread-based fabrication. In: *Proceedings of the CHI conference on human factors in computing systems*, 2024, pp.1–17. Association for Computing Machinery (ACM).

55. Takamatsu S, Yamashita T and Imai T. Fabric touch sensors using projected self-capacitive touch technique. *Sens Mater* 2013; 25: 627–634.

56. Vallett R, Young R, Knittel C, et al. Development of a carbon fiber knitted capacitive touch sensor. *MRS Adv* 2016; 1(38): 2641–2651.

57. Aigner R, Pointner A and Preindl T. Texyz: Embroidering enameled wires for three degree-of-freedom mutual capacitive sensing. In: *Conference on human factors in computing systems - proceedings*, 2021. Association for Computing Machinery. DOI: 10.1145/3411764.3445479.

58. Wu R, Ma L, Balkrishna Patil A, et al. A facile method to prepare a wearable pressure sensor based on fabric electrodes for human motion monitoring. *Text Res J* 2019; 89(23–24): 5144–5152.

59. Kuusk K, Kooroshnia M and Mikkonen J. Crafting butterfly lace - Conductive multi-color sensor-actuator structure. In: *UbiComp and ISWC 2015 - Proceedings of the 2015 ACM international joint conference on pervasive and ubiquitous computing and the proceedings of the 2015 ACM international symposium on wearable computers*, 2015, pp.595–600. Association for Computing Machinery, Inc.

60. Tan J, Chen A, Shao L, et al. Customization of e-textile sensory tools for people with dementia. *Des J* 2022; 25(1): 104–125.

61. Tan J, Bai Z, Ge L, et al. Design and fabrication of touch-sensitive polymeric optical fibre (POF) fabric. *J Text Inst* 2019; 110(11): 1529–1537.

62. Post ER, Orth M, Russo PR, et al. E-broidery: design and fabrication of textile-based computing. *IBM Syst J* 2000; 39(3.4): 840–860.

63. Al-Huda Hamdan N, Heller F, Wacharamanotham C, et al. Grabrics: a foldable two-dimensional textile input controller. In: *Conference on human factors in computing systems - proceedings*, 2016, pp.2497–2503. Association for Computing Machinery.

64. Bai VZ, Tan J, Chen A, et al. Enhancing the wearablity and accessibility of illuminated POF garment. *Int J Clothing Sci Technol* 2020; 32(2): 218–230.