

RAE2026

# 3D Knitted Structure Design for Wearable Pressure Sensors

MCO3

Prof. Annie YU

UoA38

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# Title: 3D Knitted Structure Design for Wearable Pressure Sensors

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## Project Descriptor

The rise of the Internet of Things (IoT) and wearable electronics has driven a growing demand for soft, flexible textile sensors. In particular, a fabric-based pressure sensor that can be integrated into garments, such as compression wear, intimate apparel, and tight-fit medical devices, is highly desirable, as it provides insights into treatment effectiveness and wearer comfort.

Various approaches exist for fabricating pressure sensors using textiles or soft materials. However, many of these methods face limitations: the fabrication process can be too complex for practical application, or the resulting sensors may lack stability and accuracy. This highlights a significant opportunity to improve textile pressure sensors for everyday use.

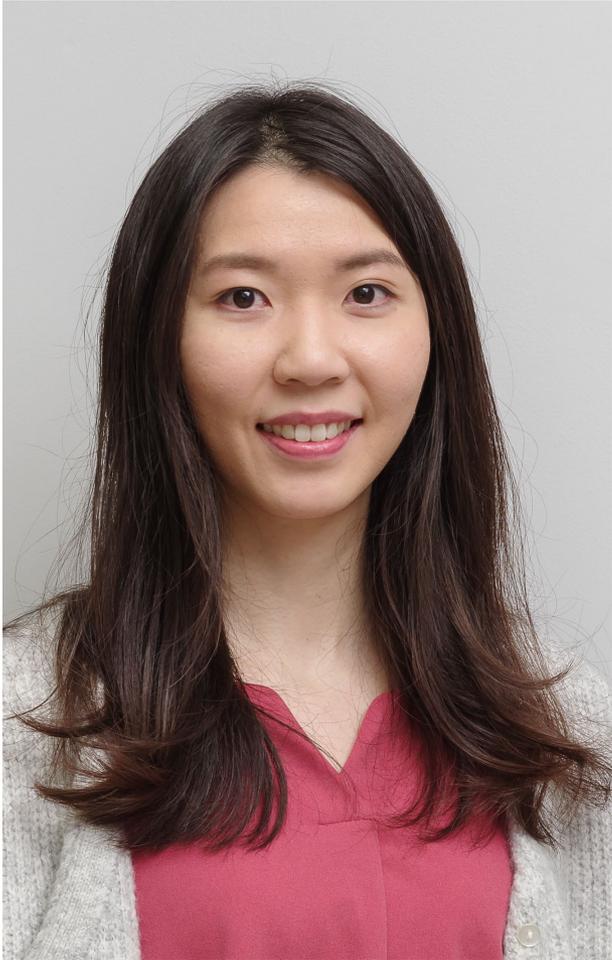
This study aims to design a novel knitted spacer fabric sensor for body pressure measurement. Conducted as a non-funded study from April 2020 to March 2023 in collaboration with Prof. Ishii Yuya from Kyoto Institute of Technology, the research introduces an innovative five-layer weft-knit fabric with a spacer structure that functions as a capacitive sensor and can be knitted in a single process. This design leverages the inherent flexibility and compressibility of knitted fabrics, representing a breakthrough in textile sensor technology. The outer layers, made from insulated yarn, ensure the sensor is safe and comfortable for skin contact. Notably, this fabric sensor can be produced on a standard double-bed weft-knitting machine in one seamless process, eliminating the need for additional coating, lamination, or assembly. This greatly simplifies both production and practical application.

The outcomes of this research open new avenues for the development of textile pressure sensors and wearable electronics. The flexible and breathable nature of the knitted sensor makes it suitable for applications in health monitoring, sports, and interactive textiles. The research findings have been disseminated through academic papers, patents, newspaper reports, and conferences.

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## Personal Profile: **Dr. Annie YU – Assistant Professor**

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Dr. Yu's research focuses on the design and development of novel knitted fabrics and functional textiles. Her expertise spans knitting technologies, apparel production techniques, experimental design, and the evaluation of clothing fit and comfort. She also investigates the physiological and psychological responses of human participants to different types of textiles and clothing products and develops simulation models to predict garment-skin pressures.

Dr. Yu is the sole Principal Investigator (PI) of the following funded projects: "Effect of Inlaid Yarns and Inlaid Method on Compression Behaviour of Weft-knitted Spacer Fabric" funded by the Kinugasa Fiber Research Centre (1 April 2020 to 31 March 2021); "Development of a 3D-Shaped Knitted Composite for Wearable Cushioned Products" funded by the Kyoto Technoscience Centre (1 April 2022 to 31 March 2023); and "Breathable Cushioning Created by Novel Multi-layer Sandwich Knitted Structure" funded by The Hong Kong Polytechnic University (1 November 2023 to 31 October 2026). The last study is ongoing and was developed as MCO1. She is also the sole PI of "Development of Anti-vibration Glove with 3D Structured Weft-knitted Fabric", funded by the Japan Society for the Promotion of Science (1 April 2020 to 31 March 2023), which contributed to MCO2. She also collaborated with Prof. Ishii Yuya from the Kyoto Institute of Technology on research related to knitted capacitance sensors, delivered as MCO3.

Dr. Yu began her academic research career at PolyU in 2023, conducting studies related to textiles and knitting design. In the same year, she received the Kinugasa Textile Award (Academic Category) from the Kinugasa Textile Research Foundation for Textile Science.

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# Research Questions

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A 3D knitted fabric, such as spacer fabric, is lightweight and offers controllable thickness and compression behaviour in the spacer layer, making it a promising material for capacitive pressure sensors. However, in practical applications, chemical coating, printing, covering, or lamination of additional materials is generally required to prevent direct contact with the human body, as the conduction of electrical current through the body could interfere with the sensor's pressure measurements. The research questions for this programme are as follows:

1. How can a soft textile sensor be fabricated in a simple, scalable way that can be readily adopted by industry?
2. How can the sensitivity and stability of textile sensors be enhanced?
3. How can textile sensors be designed to accommodate and respond to human contact or touch?
4. What kinds of design modifications or added-value functions can be incorporated into textile sensors for specific applications?

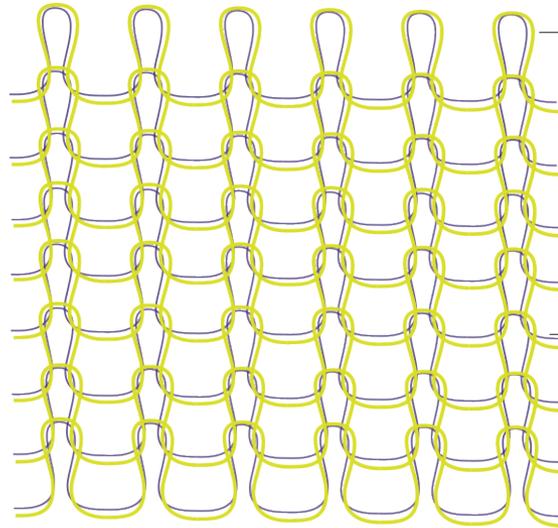
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## Research Outputs

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- A novel method for producing fabric-based capacitive pressure sensors was developed.
- A five-layer weft-knit fabric with a spacer structure was designed and produced as a capacitive sensor.
- An active signal-generating touch/pressure sensor was further developed.
- One Japanese patent was filed (#特願2021-183160)
- Two journal papers were published (<https://doi.org/10.1080/15376494.2022.2103216> , <https://doi.org/10.1088/1361-665X/acb471>).
- Three conference presentations were delivered.
  
- Dr. Yu's contributions to this research included the following:
  - Defining the design criteria and sourcing materials for the 3D knitted pressure sensors
  - Creating, designing, and fabricating the 3D knitted structures
  - Modifying and evaluating sensor parameters to optimize pressure-sensing performance

# Research Outputs: Knitting of a Five-layer Structured Capacitive Sensor

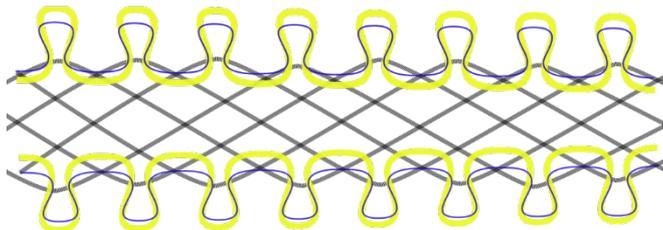


Structure of surface layers

Non-conductive yarn (yellow) appears on the outer surface of the fabric

Conductive yarn (thin dark purple) appears on the inner side of the fabric structure

Monofilament yarns connect the top and bottom surface layers by tuck stitches

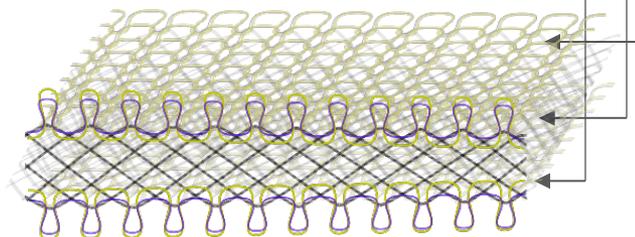
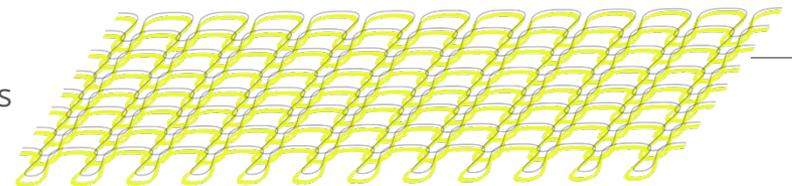
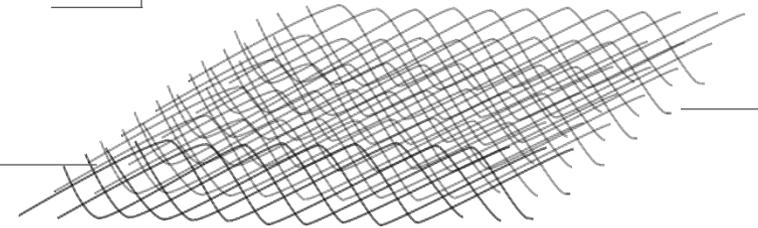
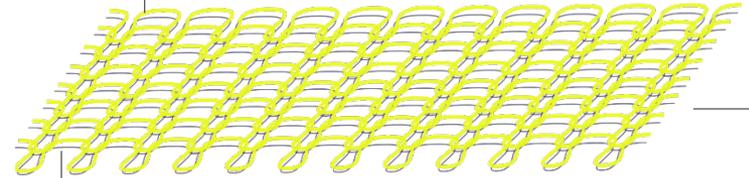


Yarn arrangement along longitudinal cross-section

Only the non-conductive yarn is visible on the fabric surface

The conductive yarn is hidden within the spacer fabric structure

Monofilament yarns support the structure and separate the two surface layers apart



# Research Outputs: Five-Layer Structured Capacitive Sensor

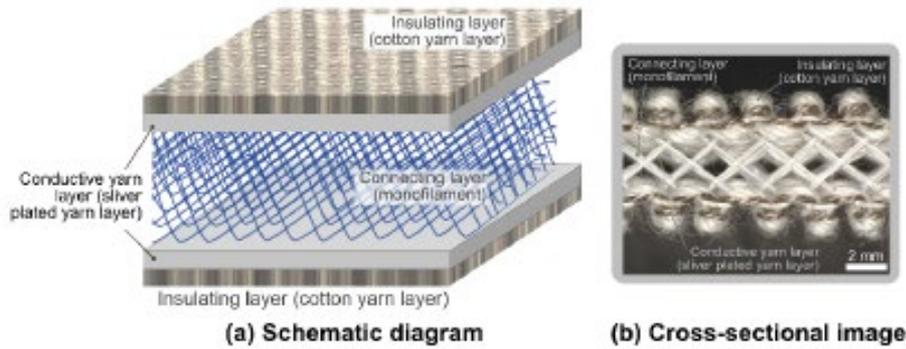


Figure 1. Five-layer structure of the textiles pressure sensor

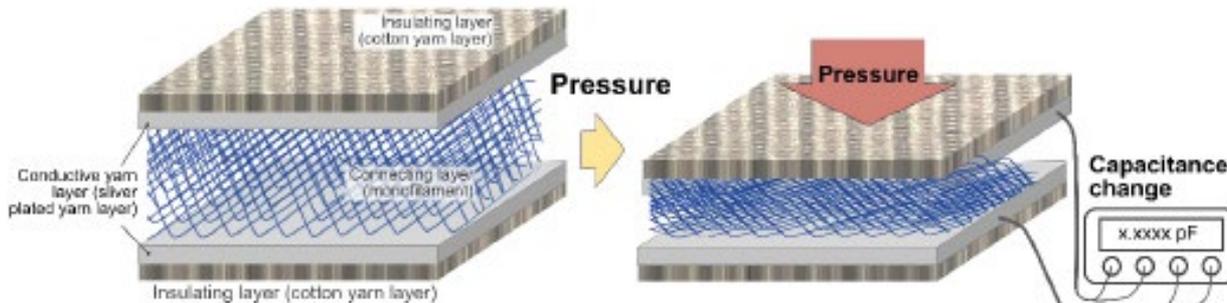
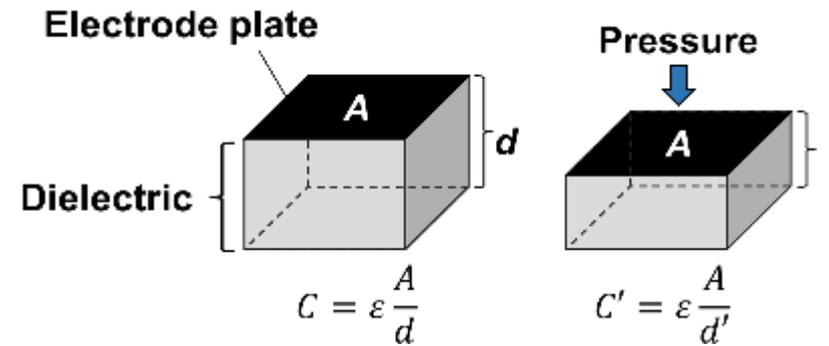
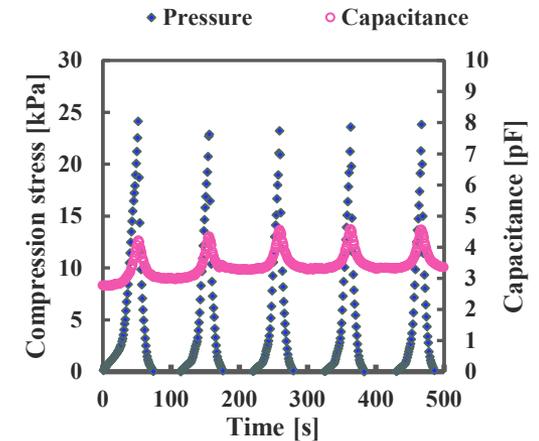
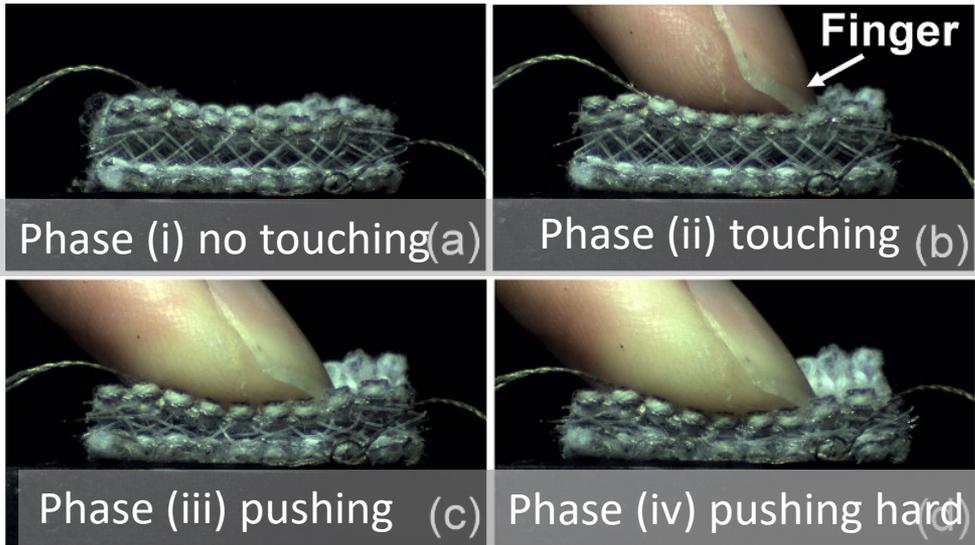


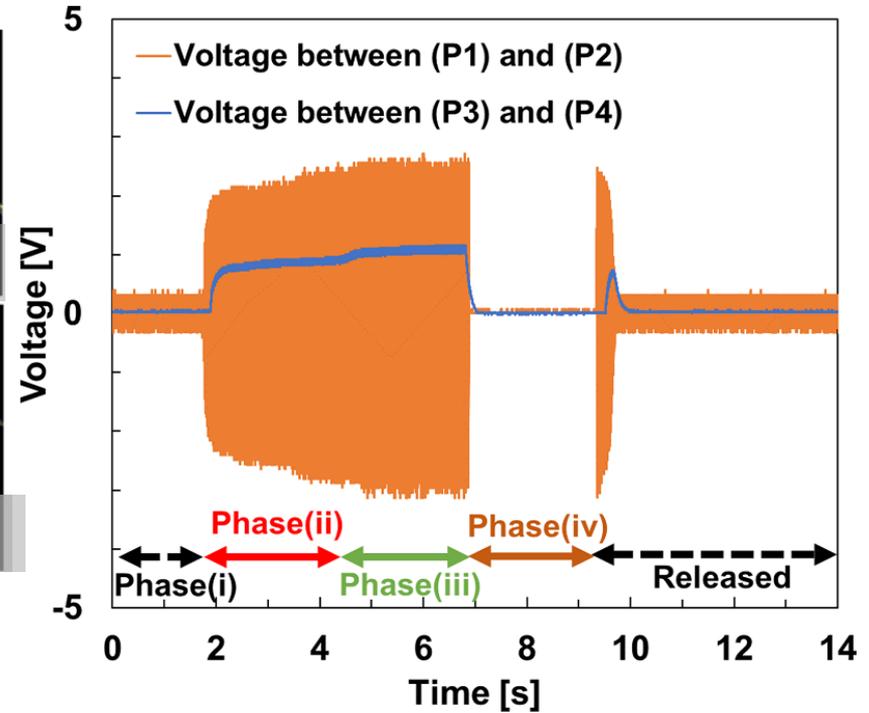
Figure 2. Fabric is compressed to change the capacitance to use for pressure detection



# Research Outputs: Active Signal-Generating Touch/Pressure Sensor



Fabric sensor at different touching/pressing phases



Output voltage from the sensor when a finger touches/presses against it at different touching/pressing phases

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## Research Field & Key References

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- Capacitive pressure sensors have been developed using multilayer woven fabrics with different weave structures and patterns of conductive and insulating yarns to form the capacitive sensor [1–3]. However, the weft yarns in the woven dielectric layer were found to affect the capacitance change rate and sensitivity of the sensor.
- As the dielectric layer largely influences the change in capacitance, another approach to producing textile-based capacitive sensors involves replacing the middle fabric layer with other materials, such as artificial fibres [4] or silicone rubber and elastomers containing sugar or salt granules [5, 6]. However, due to the presence of other materials aside from fabric, the production process becomes more complicated.

[1] T. Terada, M. Toyoura, T. Sato, et al., Functional fabric pattern-examining the case of pressure detection and localization, *IEEE Trans. Ind. Electron.*, vol. 66, no. 10, pp. 8224–8234, 2019. DOI: [10.1109/TIE.2018.2885692](https://doi.org/10.1109/TIE.2018.2885692).

[2] S. Eriksson, L. Berglin, E. Gunnarsson, et al., Three-dimensional multilayer fabric structures for interactive textiles, in *The Third Conference in 3D Textiles and Their Applications*, Wohan, China, 20110420, 2011.

[3] R. Fan, G. Chen, and Z. Pei, Design and electromechanical properties of three-layer fabric-based pressure sensor, *Text. Res. J.*, vol. 91, no. 17–18, pp. 2074–2086, 2021. DOI: [10.1177/0040517521994343](https://doi.org/10.1177/0040517521994343).

[4] C. M. Yang, T. L. Yang, C. C. Wu, et al., Textile-based capacitive sensor for a wireless wearable breath monitoring system, in *2014 IEEE International Conference on Consumer Electronics (ICCE)* 10–13 Jan., 2014, 2014, pp. 232–233.

[5] S. Fischer, C. Böhmer, S. Nasrin, et al., Flat-knitted double-tube structure capacitive pressure sensors integrated into fingertips of fully fashioned glove intended for therapeutic use, *Sensors*, vol. 24, no. 23, Article no: 7500, 2024. DOI: [10.3390/s24237500](https://doi.org/10.3390/s24237500).

[6] O. Atalay, A. Atalay, J. Gafford, et al., A highly sensitive capacitive-based soft pressure sensor based on a conductive fabric and a microporous dielectric layer, *Adv. Mater. Technol.*, vol. 3, no. 1, Article no: 1700237, 2018. DOI: [10.1002/admt.201700237](https://doi.org/10.1002/admt.201700237).

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## Research Field & Key References

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- A knitted spacer fabric has been adopted as the dielectric layer, with its two surfaces coated with conductive fabric [7], 3D-printed single-walled carbon nanotubes, and silver ink [8]. However, combining multiple layers of chemical coatings or printed materials makes the fabrication process more complex, and delamination may occur after repeated use or washing.
  - A capacitive sensor has also been developed using a spacer fabric with conductive yarns integrated into its surface layers [9]. However, the conductive yarns or materials used on the surface of fabric sensors can come into direct contact with the human body when the sensors are touched or compressed. The conduction of electrical current to and through the body could interfere with the pressure-sensing performance of the sensor.
- [7] R. Wu, L. Ma, A. Patil, et al., All-textile electronic skin enabled by highly elastic spacer fabric and conductive fibers, *ACS Appl. Mater. Interfaces.*, vol. 11, no. 36, pp. 33336–33346, 2019. DOI: [10.1021/acsami.9b10928](https://doi.org/10.1021/acsami.9b10928).
- [8] C. C. Vu and J. Kim, Simultaneous sensing of touch and pressure by using highly elastic e-fabrics, *Appl. Sci. (Switzerland)*, vol. 10, no. 3, p. 989, 2020. DOI: [10.3390/app10030989](https://doi.org/10.3390/app10030989).
- [9] D. Matsouka, S. Vassiliadis, S. Mitilineos, et al., Three-dimensional weft-knitted textile fabrics-based capacitors, *J. Text. Inst.*, vol. 109, no. 1, pp. 98–105, 2018. DOI: [10.1080/00405000.2017.1330174](https://doi.org/10.1080/00405000.2017.1330174).

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# Research Field & Key References

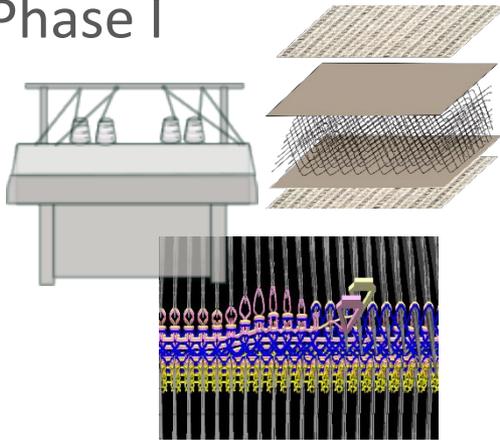
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## Knowledge Gap

- Although many research studies have been conducted on the design and development of textile-based capacitive pressure sensors, the complex fabrication methods required make adoption and industrial application challenging.
- The following knowledge gaps were identified and tackled in this research:
  - **Development of a single-process production method for fabric-based capacitive sensors**
  - **Development of a fabric capacitive sensor capable of directly sensing pressure without the need for additional covering, coating, or lamination**
  - **Development and demonstration of an innovative application of a spacer-fabric-type pressure sensor**
- This project aimed to address the identified challenges in fabricating a knitted capacitive sensor that can be in direct contact with human skin and produced through a single integrated manufacturing process.

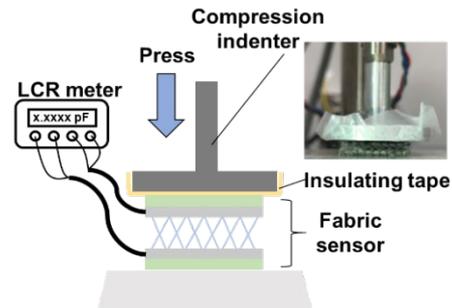
## Design of fabric sensor

### Phase I



## Evaluation

### Phase II



## Novel application

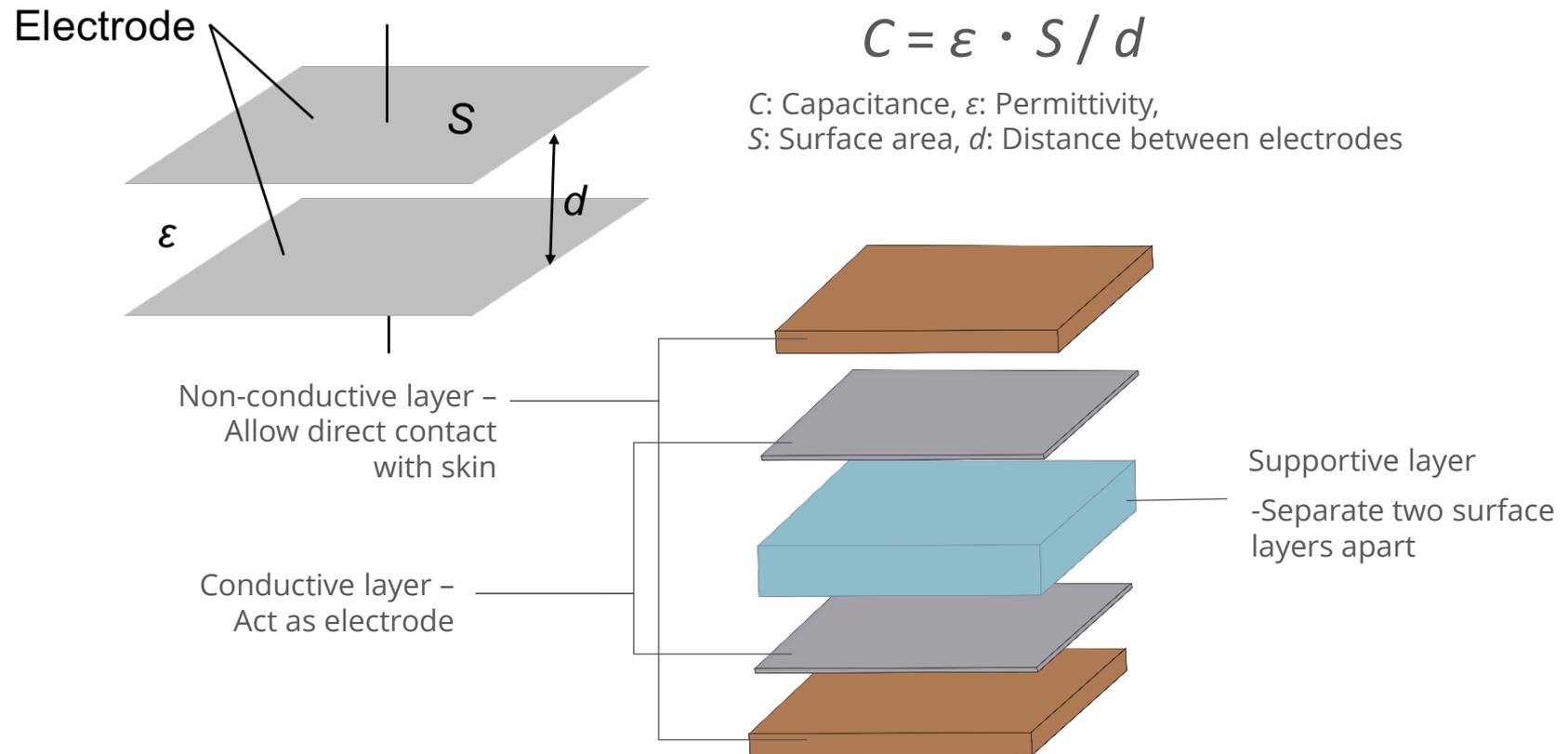
### Phase III



# Research Methods, Prototypes & Materials

## Phase I: Design of Fabric Sensor

- The fabric sensor structure is designed based on the principle of a pressure sensor utilizing the capacitive effect. An innovative approach involves applying a plating technique to form two additional outer layers, in addition to the three layers of the conventional spacer fabric.

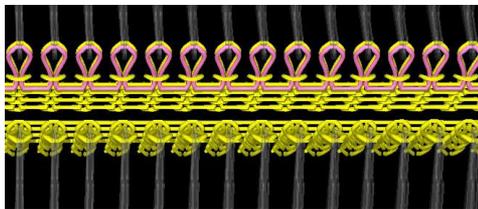


# Research Methods, Prototypes & Materials

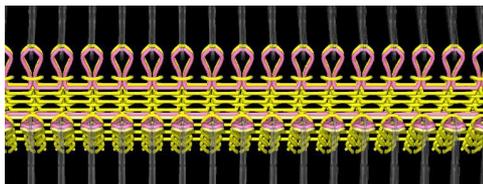
## Phase I: Design of Fabric Sensor

- An innovative approach involves applying a plating technique to form two additional outer layers, in addition to the three layers of the conventional spacer fabric.
- Different materials, knitting structures, stitch densities, and techniques are examined to create the desired five-layer structure that can perform as a pressure sensor with a single knitting process.

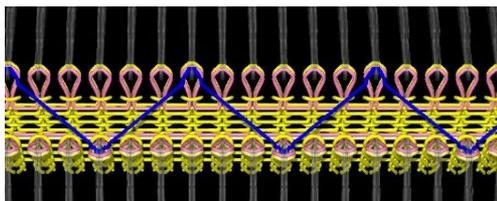
Bird view



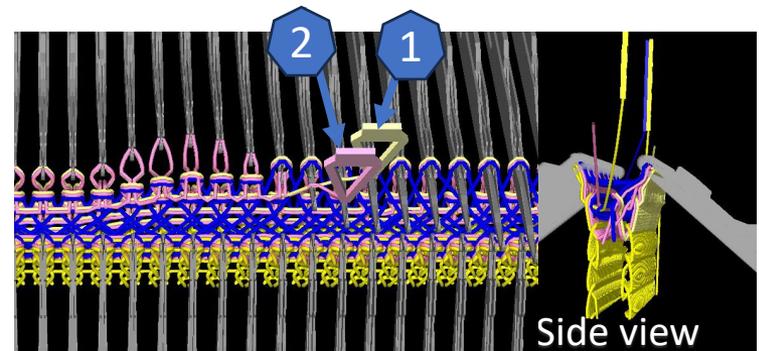
The yarns knitted on the front and back needle beds form the surface layers (yellow). An additional yarn (pink) is applied through **plating** to create an extra layer.



Four surface layers are formed using two types of yarns.



The connective yarn (blue) tucks alternately between the front and back layers to interconnect them, creating a 3D structure

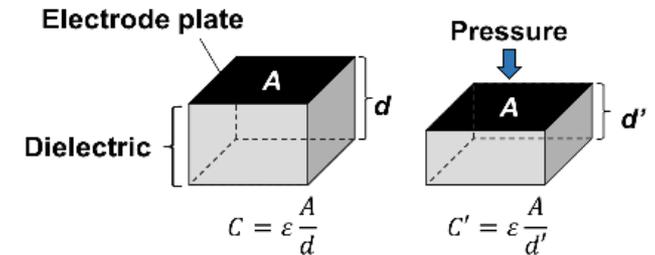
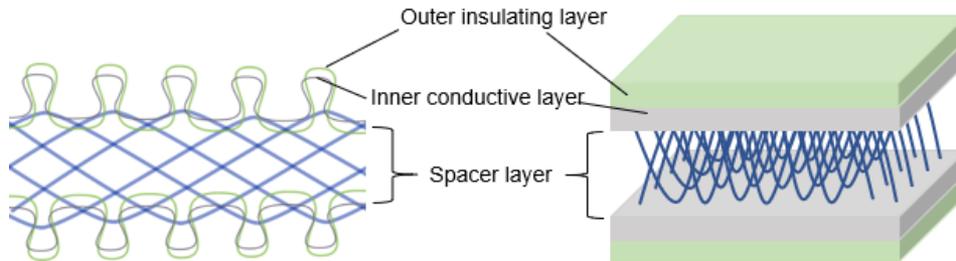


**Plating:** In the spacer structure, the surface layer is knitted using **two yarn carriers**, with the carrier for the outer yarn moving slightly ahead. As a result, one type of yarn consistently appears on the outer side, while the other remains on the inner side of the fabric.

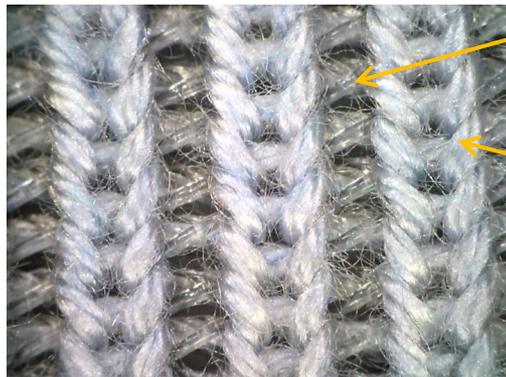
# Research Methods, Prototypes & Materials

## Phase I: Design of Fabric Sensor

- The two outer layers, made of cotton yarn, were adopted to provide insulation. The two inner layers, made of silver-coated conductive yarn, form the parallel electrode plates and are separated by a compressible spacer layer.



Conductive yarn (silver colour)



Fabric surface

Non-conductive yarn (white colour)



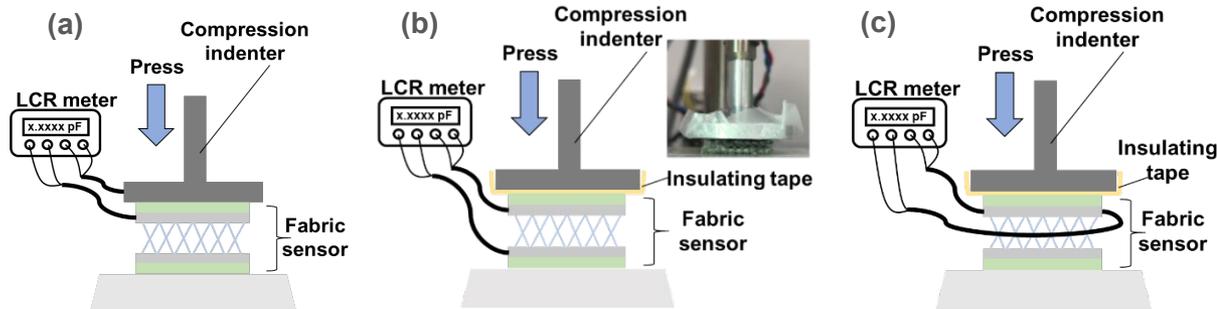
Fabric cross-section

Spacer layer  
Support and separate the upper and lower surface

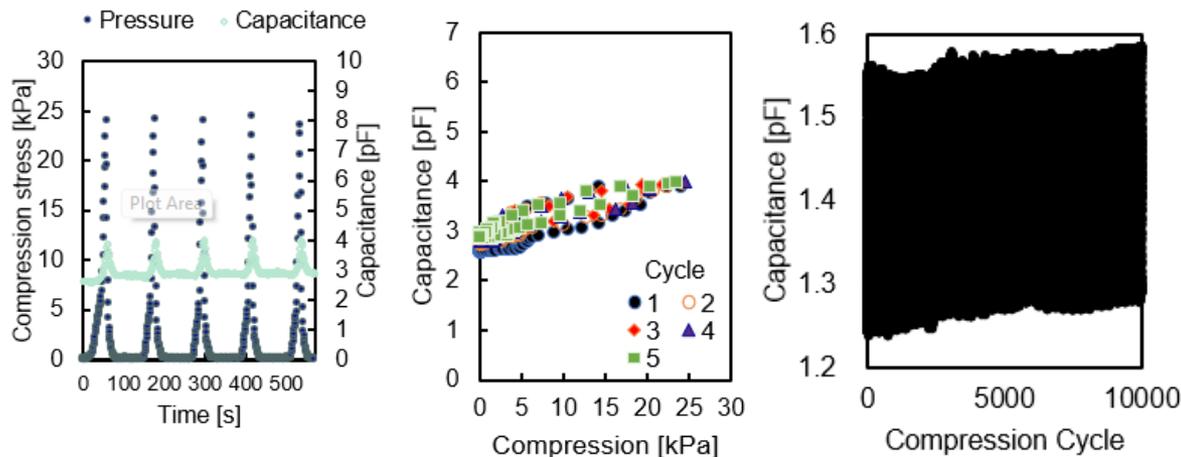
# Research Methods, Prototypes & Materials

## Phase II: Evaluation

- The effectiveness, sensitivity, and repeated use of the designed fabric pressure sensor were tested.



Measurement of the (a) insulation of the cotton surface layer, (b) change in capacitance of the fabric, and (c) electrical resistance of one of the surface layers during compression



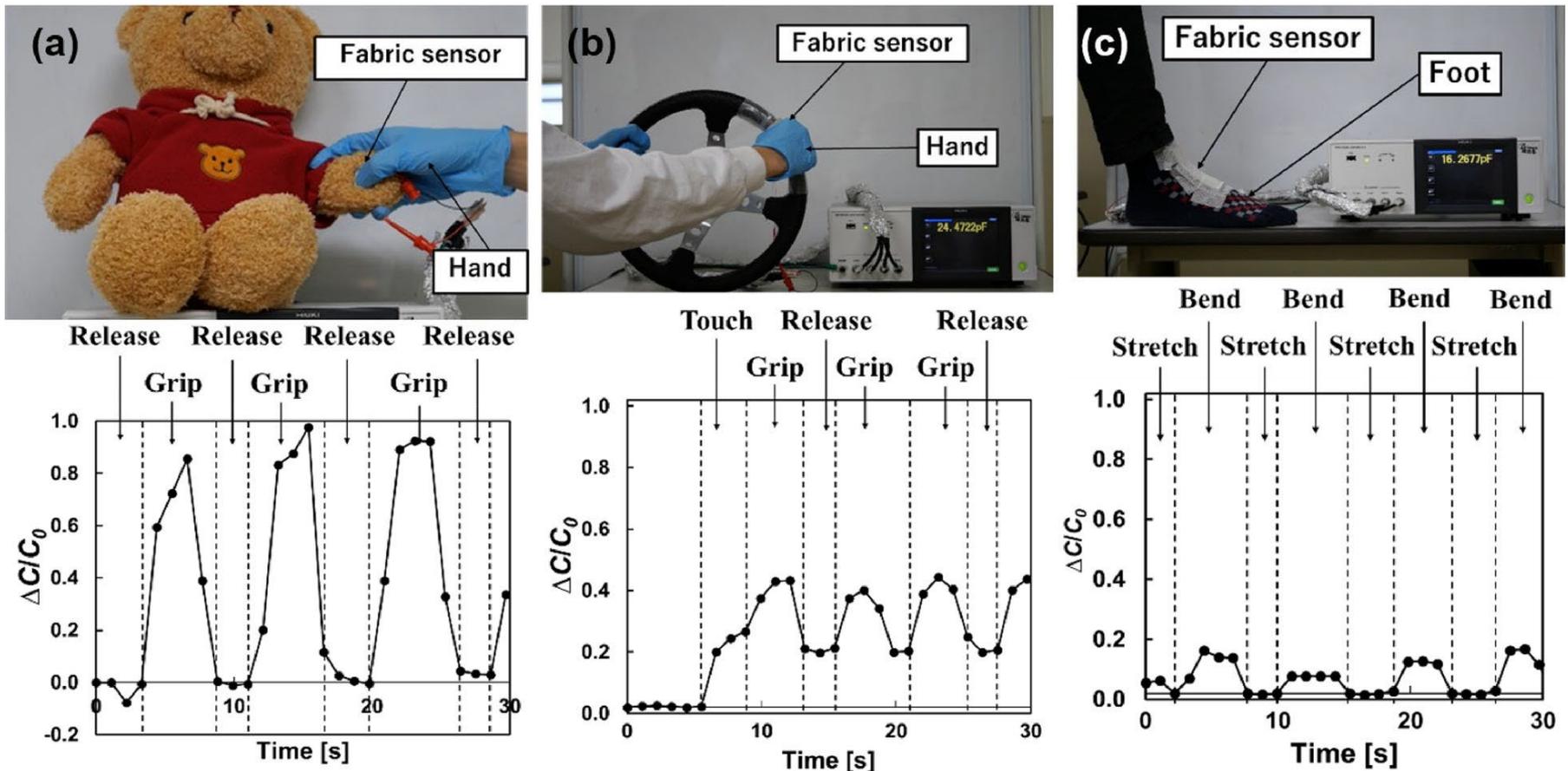
## Findings:

- The most outer insulating layers of the fabric sensor formed by plating provide high electrical resistance, thus demonstrating good insulation.
- The pressure sensing range and sensitivity of the fabric sensor can be altered by changing the contents and thickness of the spacer monofilament yarn. The fabric sensors made of polyamide monofilaments are more sensitive and have a wider range of capacitance change than those made of polyester monofilaments. The fabric sensors made with 0.08 monofilaments show a significant capacitance response at a lower pressure range than those made with 0.14 monofilaments.
- The capacitance and compression responses are more stable and reproducible after the second cycle. When the fabric sensor is compressed at a constant pressure for 10,000 times, a 1.4% increment in capacitance at no compression and 2.6% increment under 16 kPa of pressure are observed due to the deformation of the fabric.

# Research Methods, Prototypes & Materials

## Phase III: Innovative Application

- The feasibility of applying the designed fabric sensor in real application was examined.

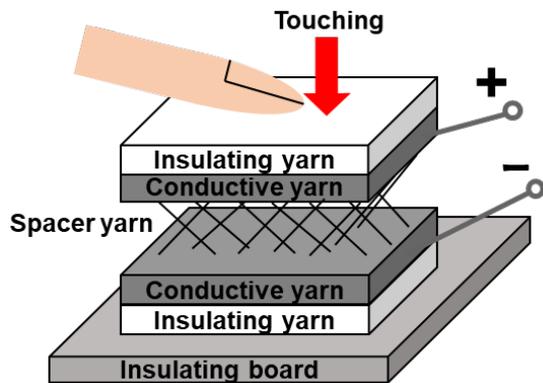


Application of the fabric pressure sensor in (a) a teddy bear, (b) a steering wheel, and (c) a sock, and the corresponding change in capacitance ratio during motion.

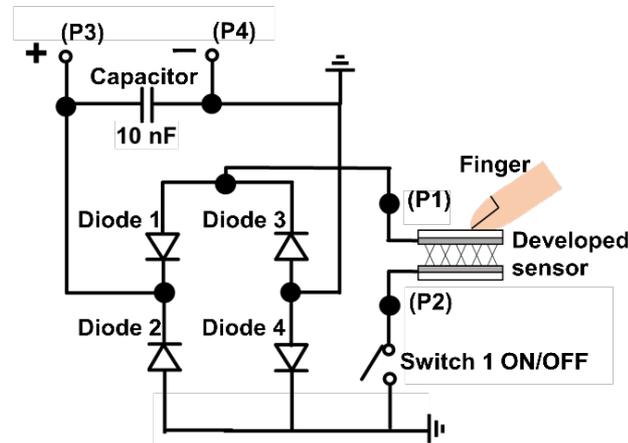
# Research Methods, Prototypes & Materials

## Phase III: Innovative Application

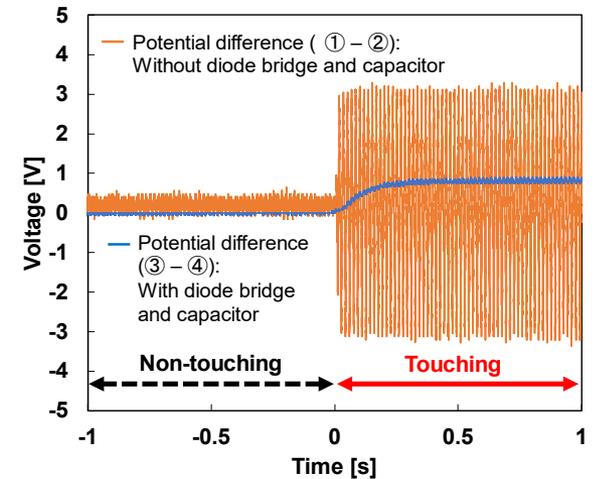
- The sensor was further developed into an active signal-generating touch/pressure sensor. The active signal is generated from electromagnetic waves present in the environment due to commercial power supplies. No additional power source is required for the fabric sensor to perform its pressure-sensing function.



Schematic of the proposed touch sensing fabric



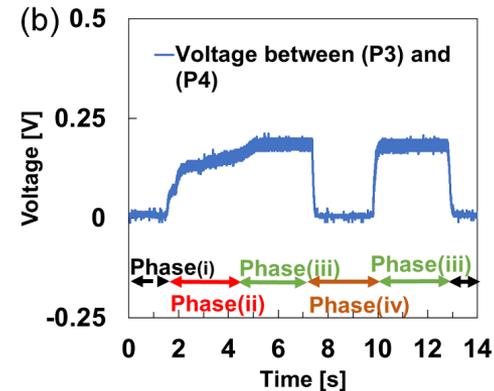
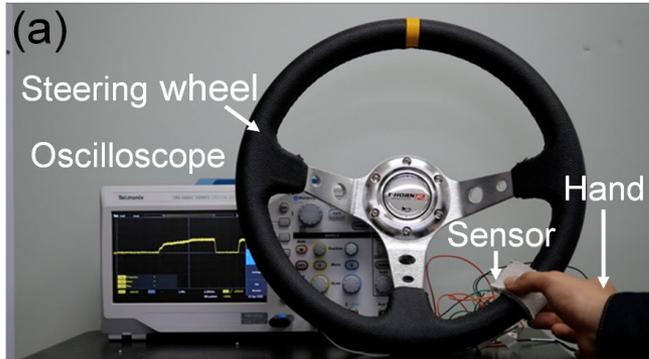
Electrical circuit for measuring the output voltage



Output voltage when a human finger touched the proposed fabric

# Research Methods, Prototypes & Materials

## Phase III: Innovative Application



(a) Image showing fingers touching/pressing a steering wheel with the developed sensor attached. (b) DC output voltage recorded when the fingers touched/pressed the steering wheel equipped with the sensor.

### Findings:

- The sensor produced different magnitudes of AC/DC voltages through the diode bridge and capacitor circuit when a person's finger performed the following actions: phase (i), no touching; phase (ii), touching; phase (iii), pushing; and phase (iv), pushing hard.
- The proposed sensor can function as both a touch and pressure sensor, and it is also capable of detecting a hard push.
- The developed sensor operates only in environments containing electrical appliances and cables. Therefore, it is suitable for use in electric or autonomous vehicles and indoor settings, where many devices are powered by AC voltage.
- The proposed sensor has the potential to contribute to the development of highly cushioned touch/pressure sensors that offer low power consumption, high air permeability, and applicability in electric and autonomous vehicles.

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## Research Outcomes, Findings & Further Research

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- The five-layer fabric structure design can successfully function as a capacitive pressure sensor, detecting pressure applied by the human body.
- Without any coating, after-treatment, or additional covering, the knitted sensor retains its softness and breathability.
- The simple single-knitting fabrication process greatly reduces production complexity, making the sensor readily scalable for industrial production.
- The innovative active signal-generating touch/pressure sensor further demonstrates the potential for advanced development and applications of 3D knitted-structure pressure sensors.
- Future studies on the construction and design of the fabric sensor are recommended to enhance its durability, stability, and sensitivity.

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# Research Dissemination

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## 2 Journal Papers

**Yu, A.**, Matsui, Y., Tonomura, K. & Ishii, Y. (2022). Development of knitted capacitive pressure sensor with spacer fabric structure. *Mechanics of Advanced Materials and Structures*. doi: 10.1080/15376494.2022.2103216

Tonomura, K., **Yu, A.** & Ishii, Y. (2023). Active signal-generating spacer-fabric-type continuous touch/pressure sensor. *Smart Materials and Structures*. doi: 10.1088/1361-665X/acb471

## 1 Japanese Patent

Name: Power generation component and touch sensor device  
(発電部材およびタッチセンサ装置)

Application number: 特願2021-183160

Submission of application date: 10 November 2021

## 3 Conference presentations

Matsui, Y., **Yu, A.** & Ishii, Y. “スペーサー構造を用いた圧力センシングファブリック” (Pressure sensing fabric using spacer structure). 2020 Autumn Research Presentation of The Society of Fiber Science and Technology Japan, held online, 6 November 2020.

Tonomura, K., Matsui, Y., **Yu, A.** & Ishii, Y. ‘スペーサーファブリックを用いた無給電タッチセンサ (Touch sensor without power supply using spacer fabric). 2021 Autumn Research Presentation of the of The Society of Fiber Science and Technology Japan, held online, 18 November 2021.

Tonomura, K., **Yu, A.** & Ishii, Y. 無給電での圧力センシングが可能なスペーサーファブリック (Spacer fabric capable of pressure sensing without power supply). 2022 Autumn Research Presentation of The Society of Fiber Science and Technology Japan, Tori Gin Bunka Kaikan, Tottori City, Tottori Prefecture, Japan, 9 November 2022.

# Research Dissemination

## News/Media Report in Japan

1. マイナビニュース 2022/08/05 08:41  
<https://news.mynavi.jp/techplus/article/20220805-2416897/>
- 2.日経XTECH, 2022年8月23日, “切る・縫う可能な織物型圧力センサー、京都工織大が糸で実現”  
<https://xtech.nikkei.com/atcl/nxt/column/18/01537/00426/>
- 3.日刊工業新聞, 2022年8月25日, “京都工織大、繊維だけの織物型圧電センサー 開発 導電性・絶縁性糸で1回編み”  
<https://www.nikkan.co.jp/articles/view/00646293>

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