RAE2026

Functional Engineering from the Design of Inlaid 3D Knitted Fabric

MCO1

Prof. Annie YU

UoA38

Contents

Title: Functional Engineering from the Design of Inlaid 3D Knitted Fabric

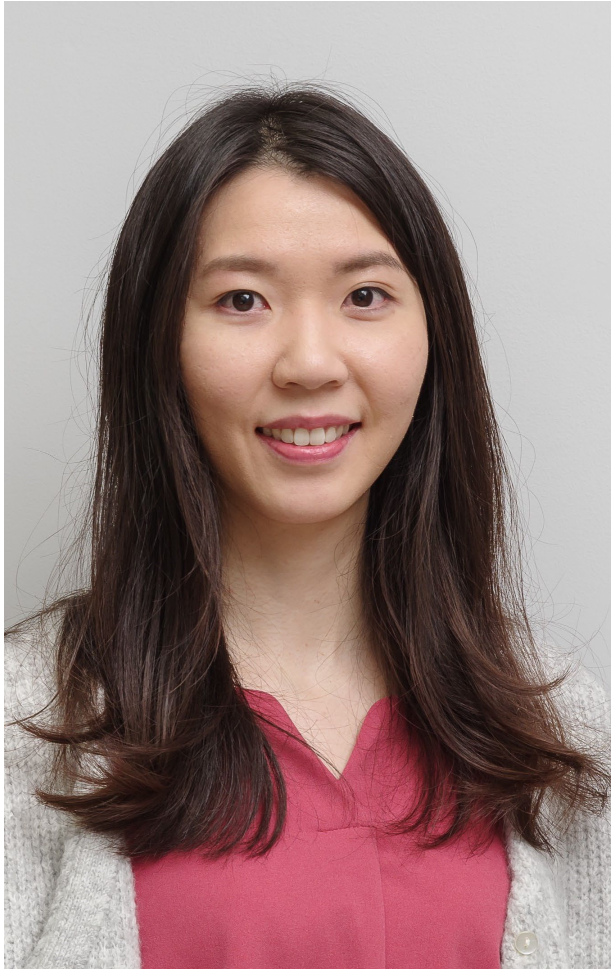
Project Descriptor

The development of 3D knitted fabrics is a pivotal area of textile research due to their unique properties and diverse applications. Spacer fabrics, a type of 3D knitted fabric, have two surface layers connected by filament yarns. Their excellent air permeability and compression resilience make them a superior alternative to elastomeric materials like cellular foam, especially in cushioning, impact absorption, and insulation applications where breathability and comfort are essential.

Despite these advantages, the knitting machine type constrains their properties: gauge affects loop size and density, while needle bed distance determines thickness. Thin weft-knitted spacer fabrics (under 1 cm) collapse easily under compression, offering limited energy absorption. Thicker yarns improve strength but increase stiffness, resulting in heavy, rigid fabrics unsuitable for wearable cushioning.

With the support of three funding schemes – the Kinugasa Fiber Research Centre (1 April 2020 to 31 March 2021), the Kyoto Technoscience Centre (1 April 2022 to 31 March 2023), and the Hong Kong Polytechnic University (1 November 2023 to 31 October 2026) – this study explored innovative structures by integrating inlay knitting into the 3D design to modify and control the shape, as well as the physical and mechanical behaviour, of weft-knitted spacer fabrics. An extensive investigation covered fabric design from yarn selection and spacer structure modification to inlay structure design and product development for practical applications. This approach offers new insights into knitted fabric development by enabling greater variation in spacer fabric properties. It allows the creation of customized materials for various textile products, including protective clothing, intimate apparel, home textiles, and medical and compression garments. By tailoring different areas of a product to exhibit specific properties, overall performance can be significantly enhanced. Research outcomes were disseminated through journal papers, conferences, exhibitions, and invited talks, underscoring the potential of this innovative approach to transform the textile industry.

Personal Profile: Dr. Annie YU – Assistant Professor



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.

Research Questions

Inlaid knitting is a technique in which extra yarns are threaded into a knitted structure.

Inlay yarns are not essential to the construction of knitted fabrics but serve to reinforce the structure and enhance its mechanical performance.

This technique holds significant potential for the novel development of 3D knitted fabrics.

However, only limited research has explored the use of inlay knitting to engineer the properties of spacer fabrics.

The present study addresses the following research questions:

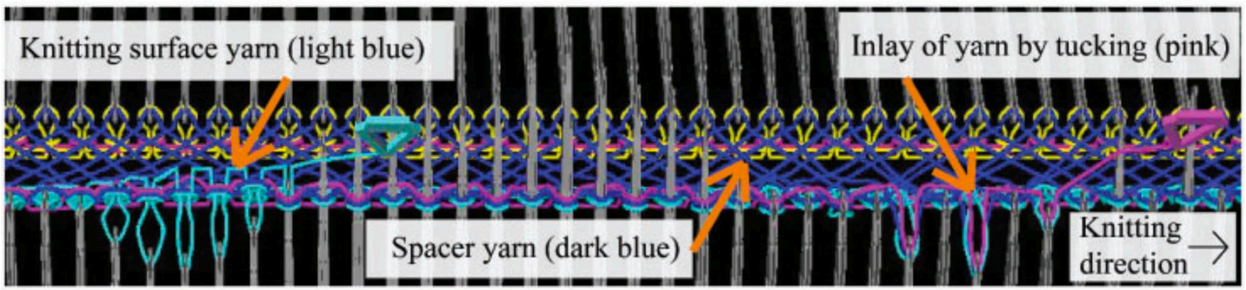
1. What inlay methods are feasible for weft-knitted spacer fabrics to modify their properties?
2. How does inlay knitting influence the structural characteristics and mechanical properties of spacer fabrics?
3. What techniques can be used to alter the shape and curvature of spacer fabrics to conform to the human body for wearable applications?
4. How can inlay knitting be utilized to control and optimize the properties of spacer fabrics?
5. In what ways can the developed fabrics contribute to performance improvement or enhancement in practical applications?

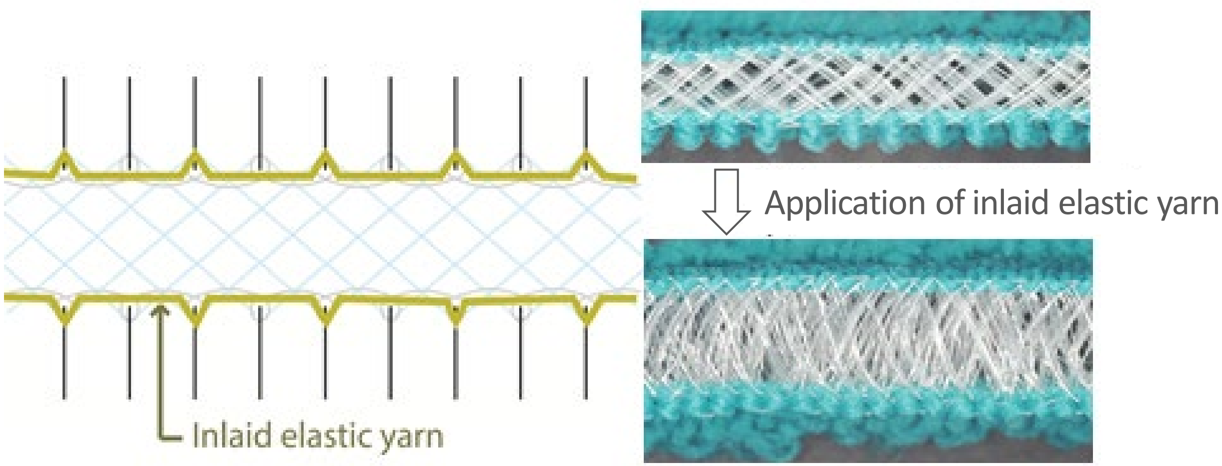
Research Outputs

- The use of inlaid elastic yarns on the surface layers of spacer fabrics to modify fabric thickness and properties has been successfully demonstrated.
- A method for controlling the curvature of spacer fabrics through the feeding rate of elastic inlay yarns has been developed.
- An approach for inlay knitting silicone tubes into the spacer fabric structure to enhance compression resistance and impact absorption has also been established.
- Prototypes of insoles, bra cups, and knee padding made from the developed fabrics have been designed and evaluated.
- Eleven Journal papers have been published.
- Five conference presentations have been delivered.

Research Outputs

- **New method of using elastic inlay for modifying thickness and properties**

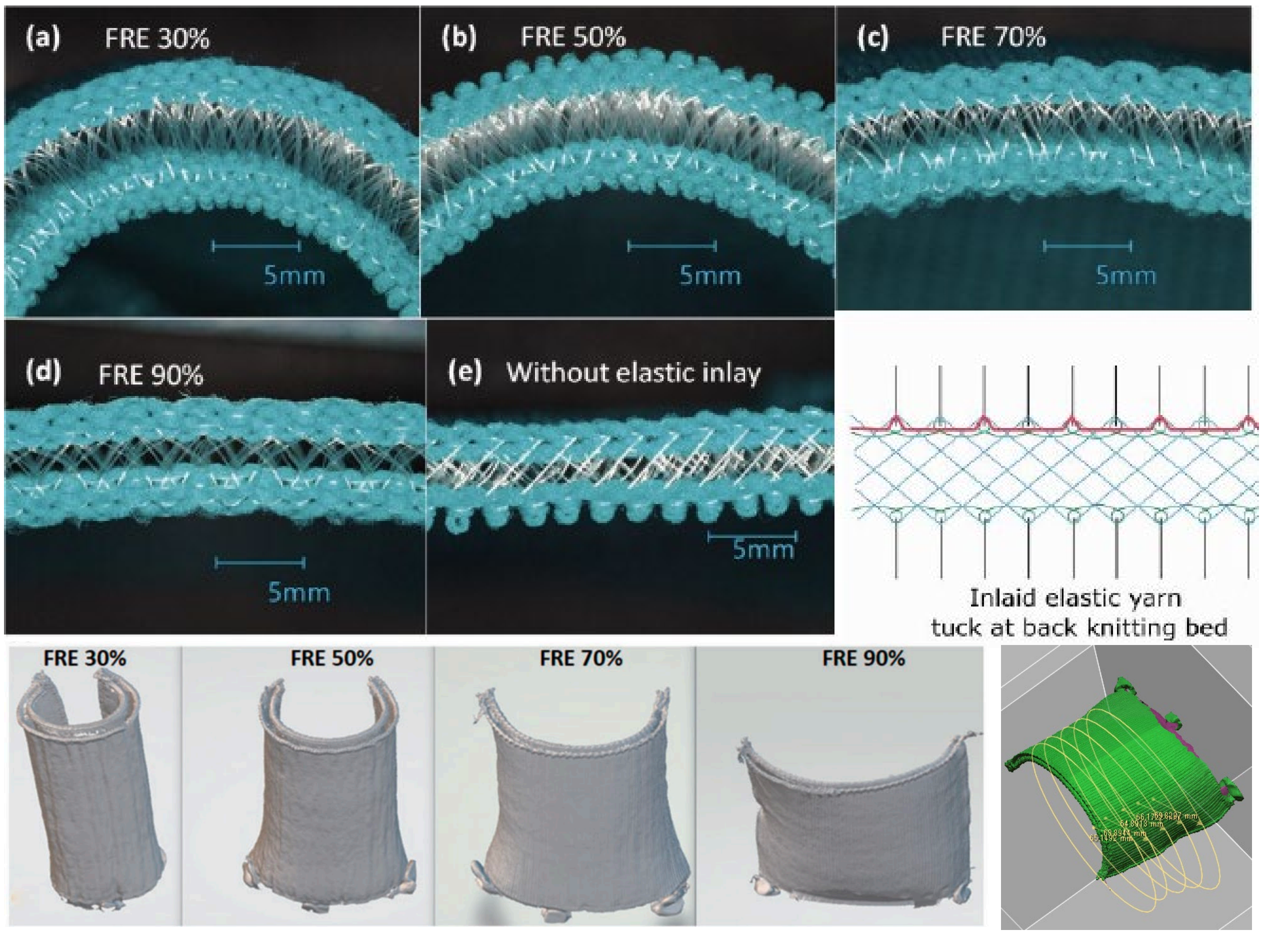




An elastic inlay on the surface layer of spacer fabric was employed to facilitate the modification of its physical and mechanical properties. The results showed that spacer fabrics with varying thicknesses, densities, and compression behaviours could be produced by using different inlay patterns and elastic yarns. Increasing the number of miss stitches in the inlay pattern contributed to greater fabric thickness and stiffness, enabling the material to withstand higher compression forces. The incorporation of elastic inlay also improved the vibration isolation properties of the fabric. This method provides a flexible approach to designing spacer fabrics with tailored performance characteristics.

Research Outputs

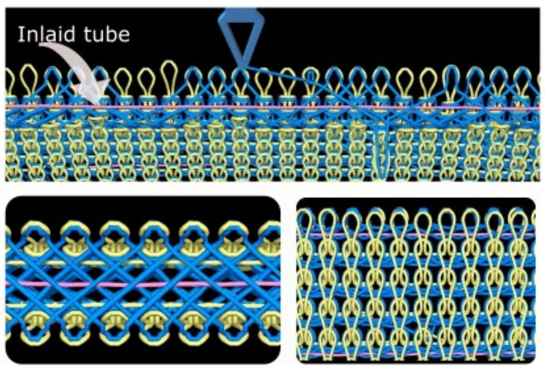
- **Elastic inlay for compression and curvature control by using inlay yarn feeding rate**



When elastic inlay yarns are incorporated into one of the surface layers of a spacer fabric, a curvature can be formed that conforms to human body contours. The feeding rate of the elastic yarn and the degree of curvature exhibited a linear relationship. Spacer fabrics produced with a lower feeding rate displayed a greater degree of curvature and increased thickness, but reduced fabric width, weight, and density. This method offers a promising approach for developing personalized protective garments and wearable devices.

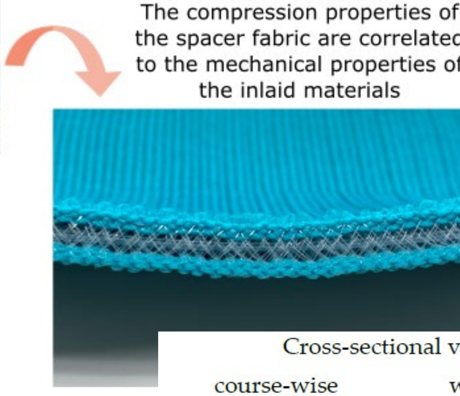
Research Outputs

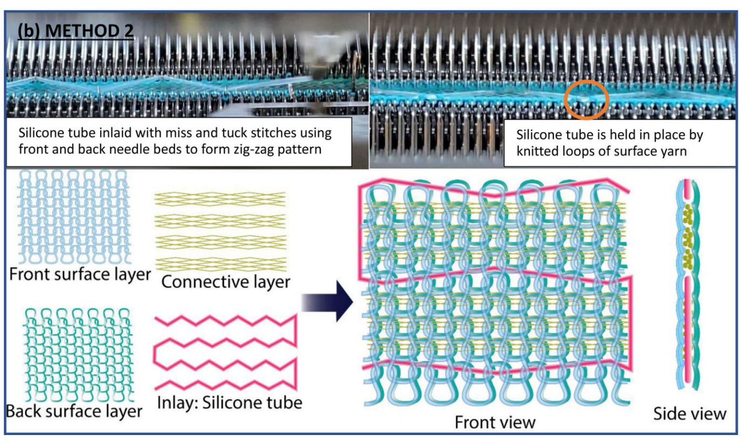
- **Novel 3D knitted structures with silicone tube inlay to improve compression resistance and impact absorption**

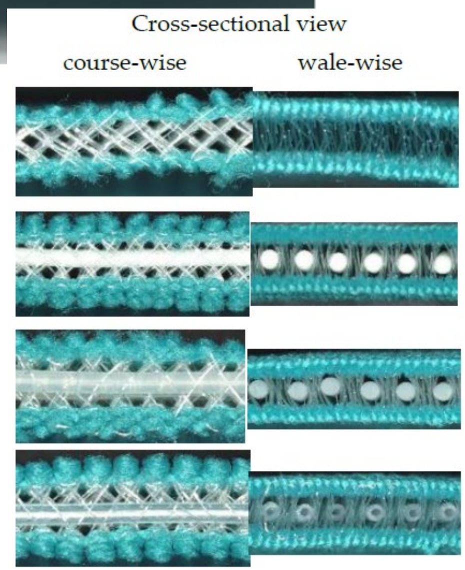


Knitting of the inlaid tube

The compression properties of the spacer fabric are correlated to the mechanical properties of the inlaid materials





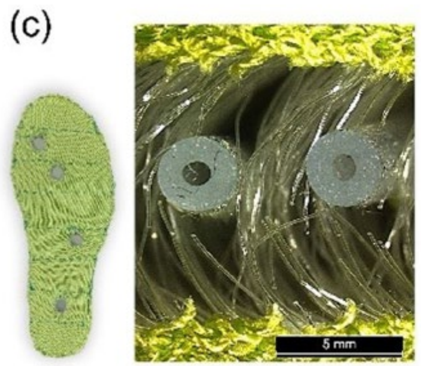


Spacer fabrics with silicone tube inlays demonstrate significantly improved compression resistance and impact force absorption. The compression behaviour of the fabric can be tailored by varying the inlay patterns and stitch densities. Incorporating silicone tubes into the structure reinforces the fabric and enhances its performance as a cushioning material.

Research Outputs

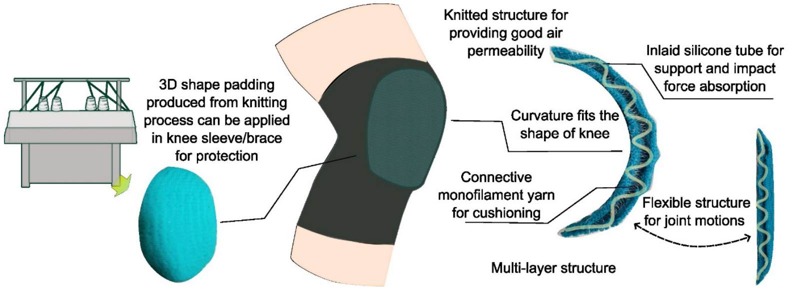
- **Prototypes for different applications**

- 3D knitted insole for enhancing footwear thermal comfort



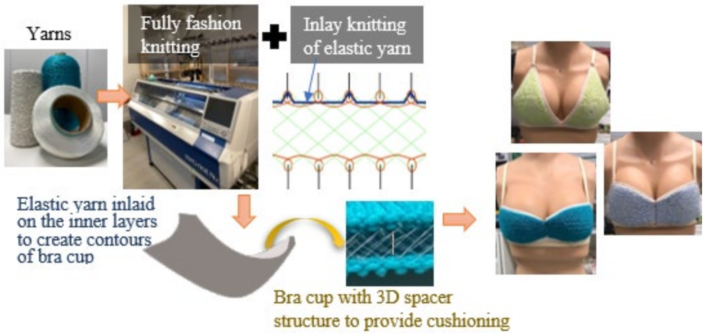
A novel textile-fabricated insole material with a 3D weft-knitted spacer structure and a silicone tube inlay offers good porosity and breathability for improving the footwear microclimate. In comparison to polyurethane (PU), 3D printed thermoplastic polyurethane (TPU), and leather insoles, a significant reduction in the relative humidity of the skin of the sole (3.21%) and heel (24.41%) of the 3D knitted insole is found. The findings are a valuable reference for the fabrication of insoles or footwear using 3D knitting with higher wear comfort.

-3D knitted padding for wearable cushioning in knee protector



A novel knitted composite has been developed, consisting of soft surface layers, a shock-absorbing middle layer made of monofilaments and silicone inlays, and additional elastic inlays in the surface layers to conform to body contours. Knitted padding incorporating silicone inlays demonstrated enhanced impact force absorption, showing a 14% improvement compared to padding without the inlay.

-Fully fashioned knitted spacer fabric bra cup



By combining fully fashioned knitting with inlay-based curvature control in 3D spacer fabrics, 3D knitted bra cups were developed to reduce material waste. Adjusting surface yarn parameters allows precise control of pressure and breast displacement. These results lay the foundation for one-step production of 3D knitted padding and personal protective devices.

Research Field & Key References

- The impact of fabric parameters on the physical and mechanical properties of spacer fabrics has been extensively studied. Factors such as thickness, flexural rigidity, the number and inclination of filaments in the connective layer, and the distance between the two outer layers directly influence compression behaviour [1–3].
- Various design modifications have also been explored. Shape memory alloys have been used as spacer yarns to enhance the energy absorption of weft-knitted spacer fabrics [4]. Steel wire twisted with high molecular weight polyethylene has been employed to improve protection against mechanical risks [5]. Multifilaments in the connective layer have been applied for thermal insulation [6], and the surface layers have been altered from plain to tuck or miss structures to modify compression behaviour [7, 8].
- Although the influence of inlay yarns on weft-knitted fabrics has been investigated [9], their application in spacer fabrics for property modification remains unexplored.

[1] Hou, X., H. Hu, and V.V. Silberschmidt, *A study of computational mechanics of 3D spacer fabric: Factors affecting its compression deformation.* Journal of Materials Science, 2012. **47**(9): p. 3989–3999.

[2] Zhao, T., et al., *Cushioning properties of weft-knitted spacer fabrics.* Textile Research Journal, 2018. **88**(14): p. 1628–1640.

[3] Bueno, M.A., *Structure and mechanics of knitted fabrics*, in *Structure and Mechanics of Textile Fibre Assemblies*, P. Schwartz, Editor. 2008, Woodhead Publishing. p. 84–115.

[4] Hamedi, M., P. Salimi, and N. Jamshidi, *Improving cushioning properties of a 3D weft knitted spacer fabric in a novel design with NiTi monofilaments.* Journal of Industrial Textiles, 2020. **49**(10): p. 1389–1410.

[5] Krauledaitė, J., et al., *Development and evaluation of 3D knitted fabrics to protect against mechanical risk.* Journal of Industrial Textiles, 2019. **49**(3): p. 383–401.

[6] Chen, C., et al., *Analysis of physical properties and structure design of weft-knitted spacer fabric with high porosity.* Textile Research Journal, 2018. **88**(1): p. 59–68.

[7] Asayesh, A. and M. Amini, *The effect of fabric structure on the compression behavior of weft-knitted spacer fabrics for cushioning applications.* The Journal of the Textile Institute, 2020: p. 1–12.

[8] Asayesh, A. and M. Amini, *Analysis of the compression performance of weft-knitted spacer fabrics for protective applications in view of the surface layer structure.* Fibers and Polymers, 2021. **22**(12): p. 3469–3478.

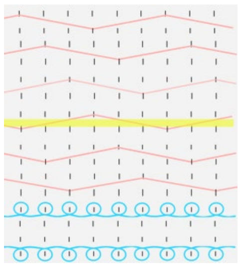
[9] Muraliene, L. and D. Mikucioniene, *Influence of structure and stretch on air permeability of compression knits.* International Journal of Clothing Science and Technology, 2020. **32**: 825–835.

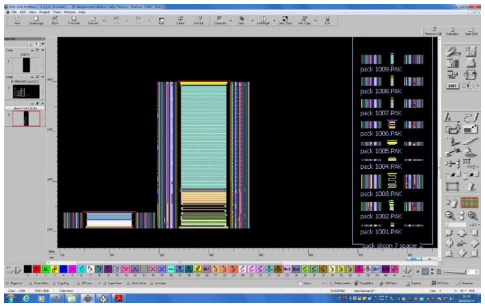
Research Field & Key References

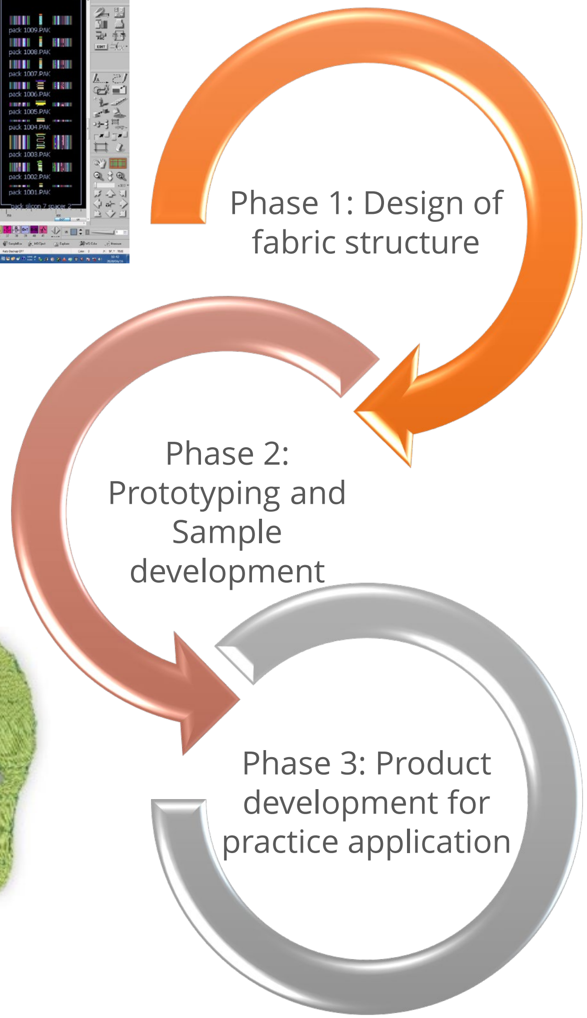
Knowledge Gap

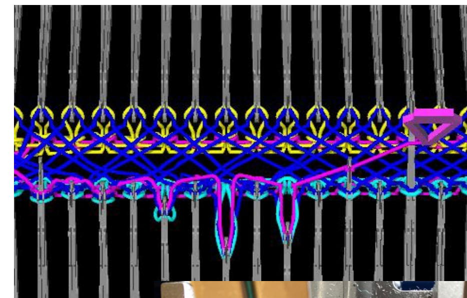
- Although much research has been conducted to understand the impact of fabric parameters on fabric performance, specifically compression behaviour, prior studies have focused on the conventional spacer fabric structures.
- The compression stiffness of spacer fabrics is largely determined by the connecting filament yarns, which limits the ability to achieve desired compression or energy absorption characteristics.
- Some novel developments in spacer fabrics have been explored; however, these have largely been restricted to the use of special functional materials within conventional structures.
- The following knowledge gaps were identified:
    - **The effect of inlay yarn types and patterns on the physical and compression properties of spacer fabrics remains unexamined due to a lack of studies.**
    - **Alternative methods, beyond the connecting filament yarn, for adjusting compression behaviour or other mechanical properties have not been explored.**
    - **Investigations into controlling the shape and curvature of spacer fabrics to conform to human body contours are also lacking.**
- This project focuses on applying inlaid knitting to spacer fabrics to create novel structures capable of modifying and controlling the shape and properties of 3D knitted fabrics, thereby expanding their potential applications in wearable products.

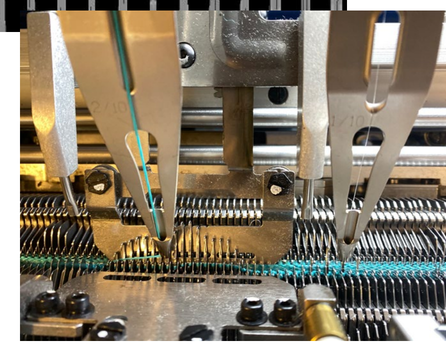
Research Methods, Prototypes & Materials

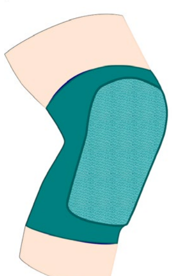


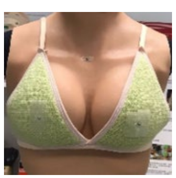










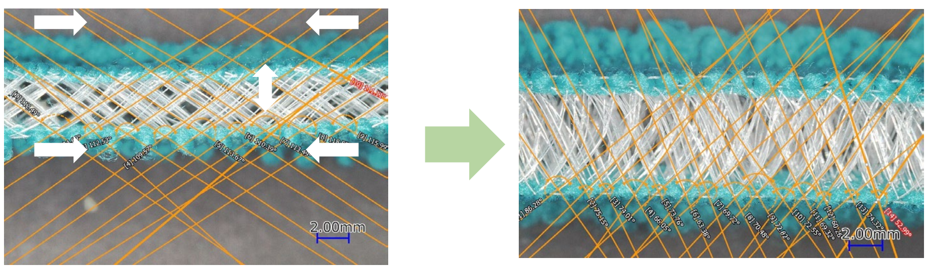


Research Methods, Prototypes & Materials

- **Phase 1: Design of Fabric Structure**

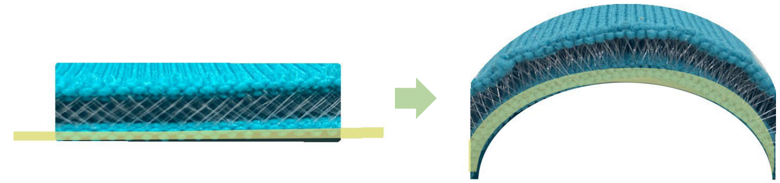
  - Design approach 1: Inlay of elastic yarn on surface layer → alter surface fabric density → change inclination angle of connective filament → change fabric thickness and compression properties

    (refer to https://doi.org/10.1177/1528083720947740)



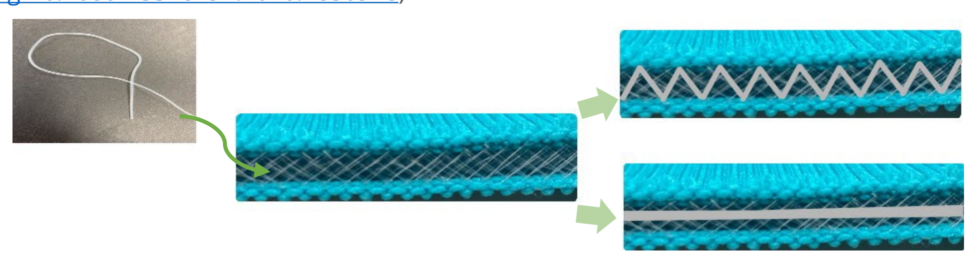
  - Design approach 2: Inlay of elastic yarn on one surface layer → alter surface fabric density → bring a curvature

    (refer to https://doi.org/10.1177/00405175221097098)



  - Design approach 3: Inlay of silicone tubular materials → support the 3D structure → maintain a soft touch and reinforce the structure to prevent collapse under compression

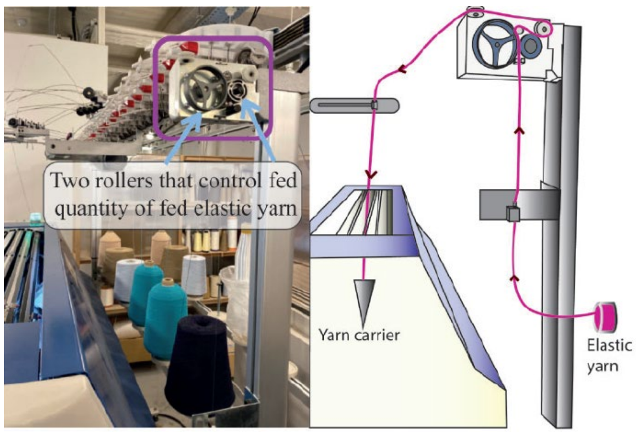
    (refer to https://doi.org/10.1080/15376494.2020.1850948)

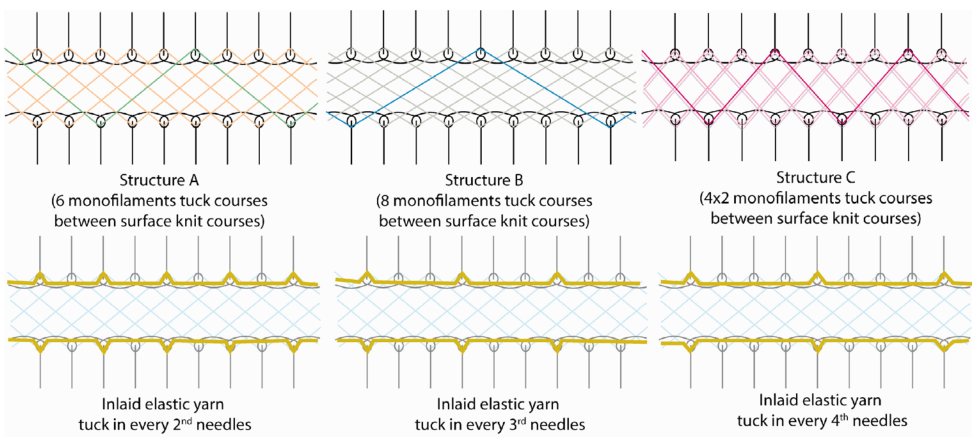


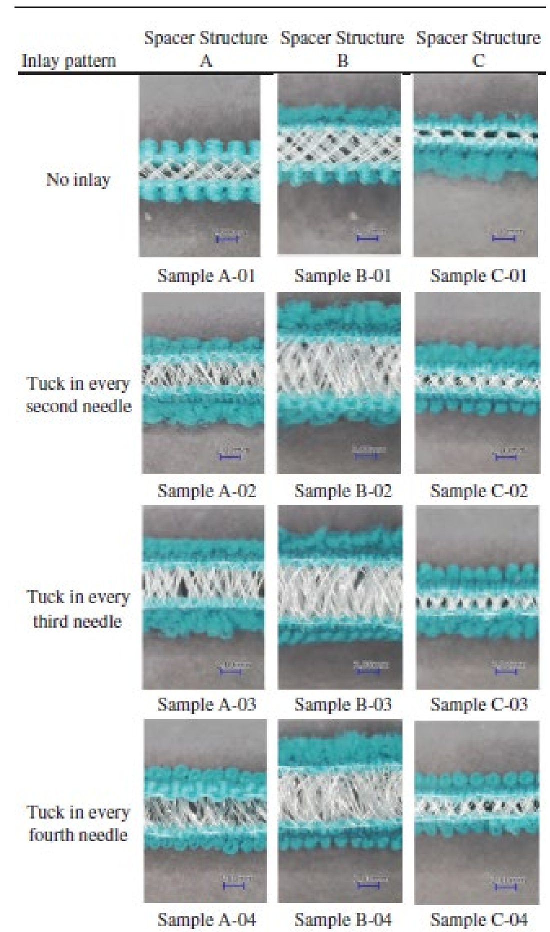
Research Methods, Prototypes & Materials

- **Phase 2: Prototyping and Sample Development**

  Develop samples to investigate: "How can inlay be applied to spacer fabrics, and what is the impact of elastic inlay on spacer fabrics with different connective structures?"





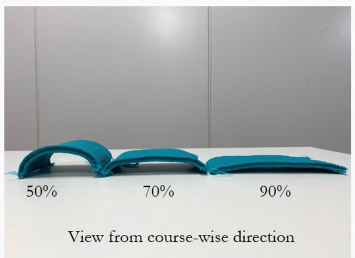


Research Methods, Prototypes & Materials

- **Phase 2: Prototyping and Sample Development**

Develop samples with control on bi-axial curvature through controlling the elastic inlay yarn feeding rate

Applied elastic inlay in course direction to give curvature



- Surface yarn: PET 450D
- Spacer yarn: PA 0.12mm monofilament
- Inlaid elastic yarn: Spandex 140D
- Tension of the elastic yarn is controlled by feeding the elastic yarn in a defined % to the knitting width

1

Modify the fabric structure to give a curvature in wale direction

2

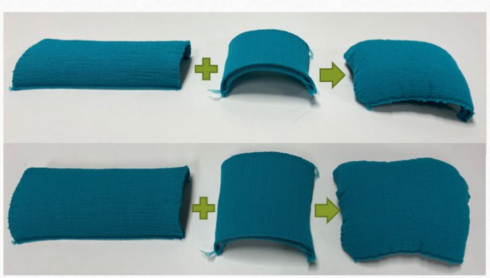

View from wale-wise direction


View from course-wise direction

- An imbalance structure with larger number of courses in one side of the fabric

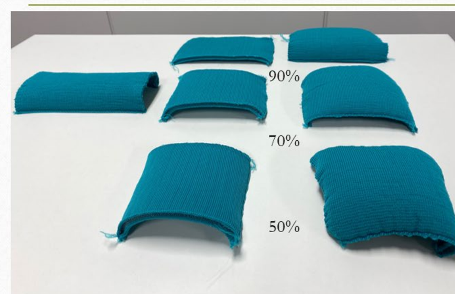
Combining the two technique to form a Bi-axial curvature

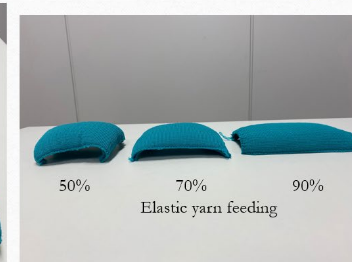
3



4

Bi-axial curvature created with different elastic yarn Feeding %

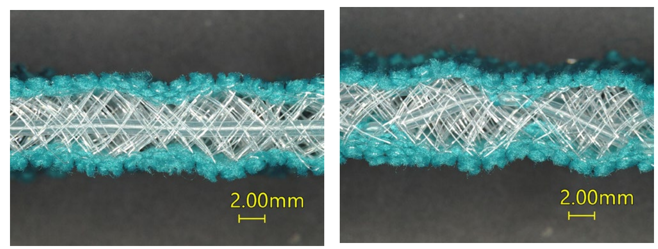


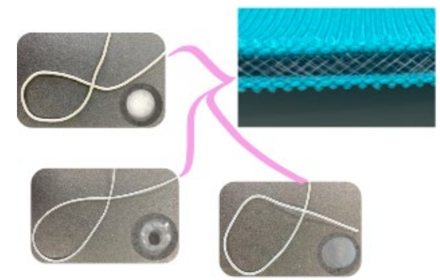


Research Methods, Prototypes & Materials

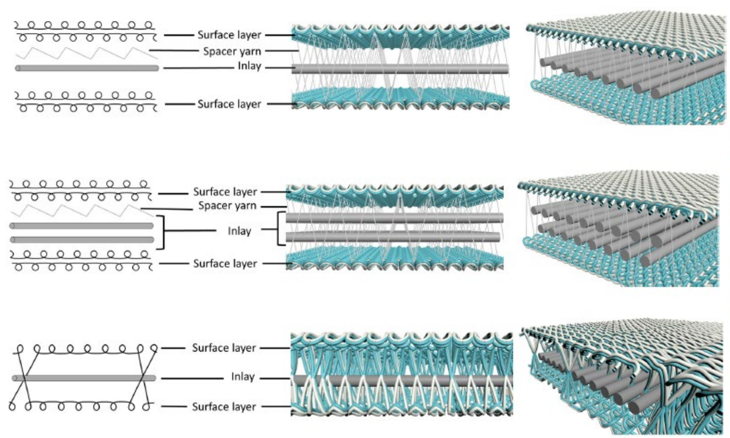
- **Phase 2: Prototyping and Sample Development**

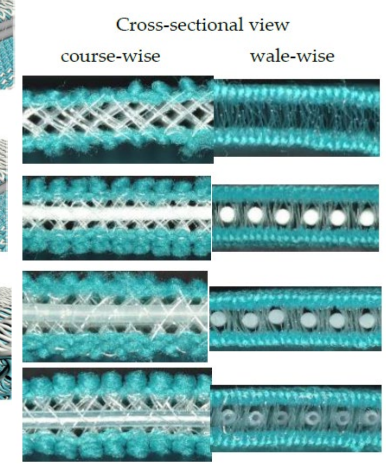
Develop samples to investigate: “What is the impact of silicone tube inlay patterns and materials on spacer fabric properties, particularly compression behaviour and impact force absorption?”





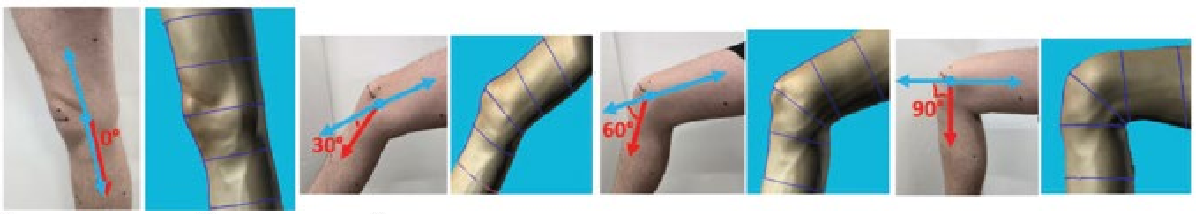
Different silicone-based tubes are inlaid into the connective layer of spacer fabrics



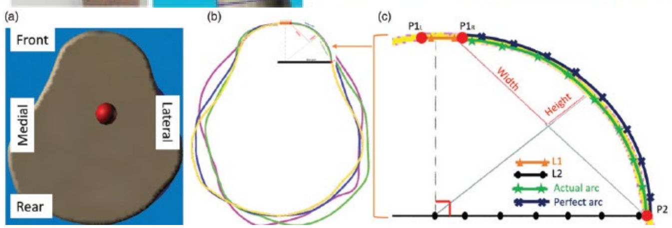


Research Methods, Prototypes & Materials

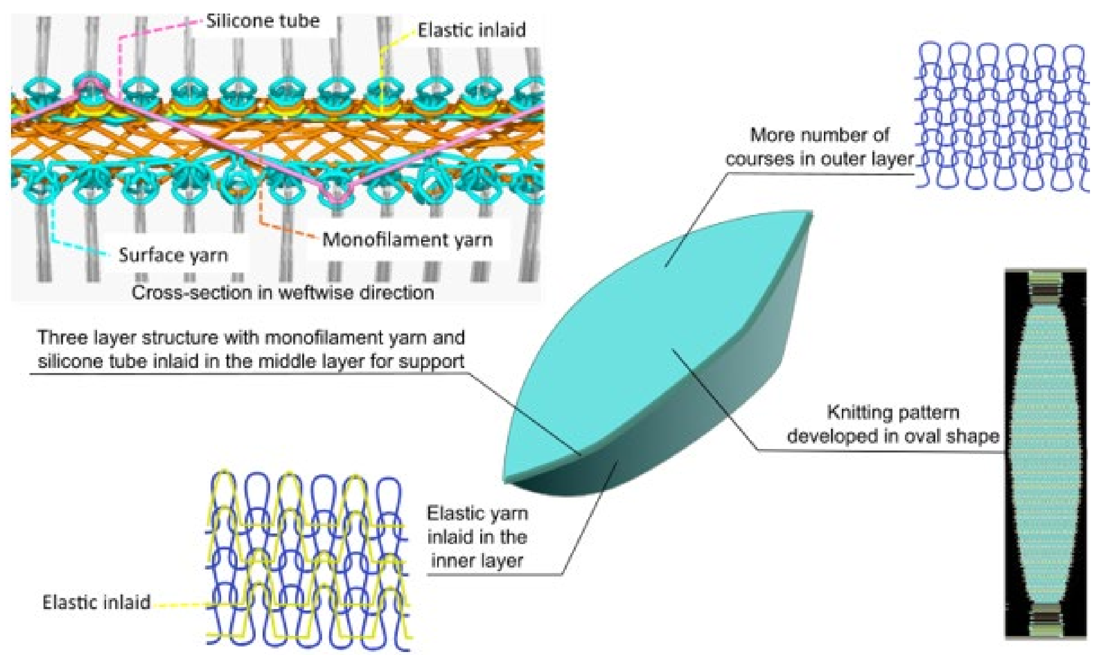
- **Phase 3: Novel Application**



Elastic knee padding was developed using the inlaid fabric in combination with fully fashioned knitting techniques.

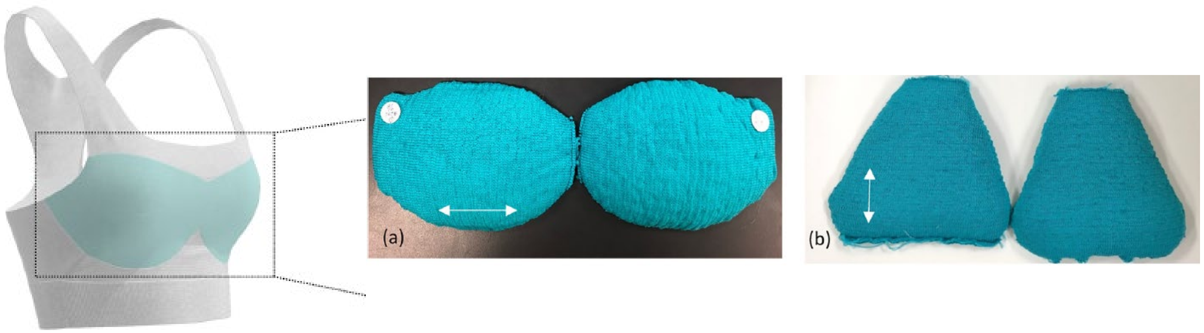


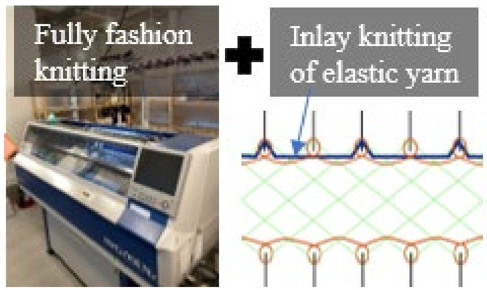
Due to the change in knee geometry during motions (refer to https://doi.org/10.1177/004051752412561), it is difficult for the current thick, rigid inelastic knee brace to fit perfectly onto the knee especially when bending.

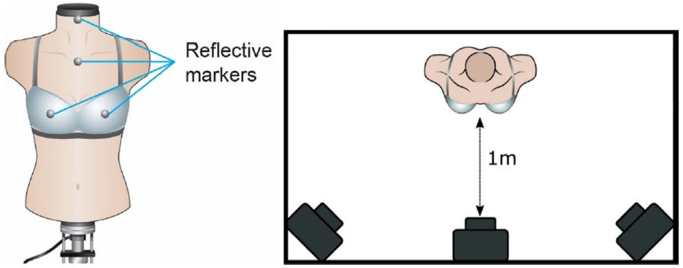


Research Methods, Prototypes & Materials

- **Phase 3: Novel Application**





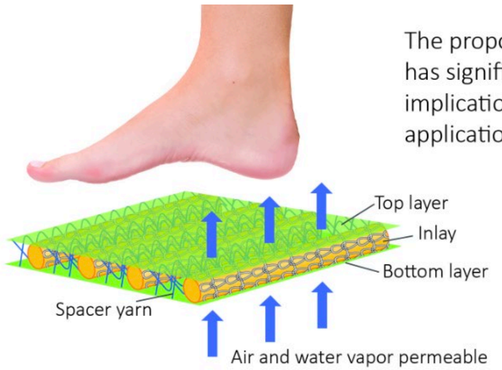


Elastic inlay combined with fully fashioned knitting was used to shape the bra cups to fit the human body. The cups exhibit excellent air permeability and are formed in a single process from yarns, reducing resource consumption and production waste, thereby supporting a more sustainable manufacturing process.

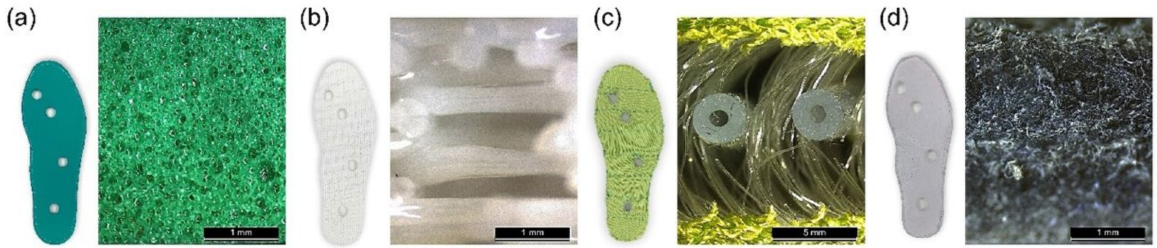
(refer to https://doi.org/10.1016/j.matdes.2022.110825)

Research Methods, Prototypes & Materials

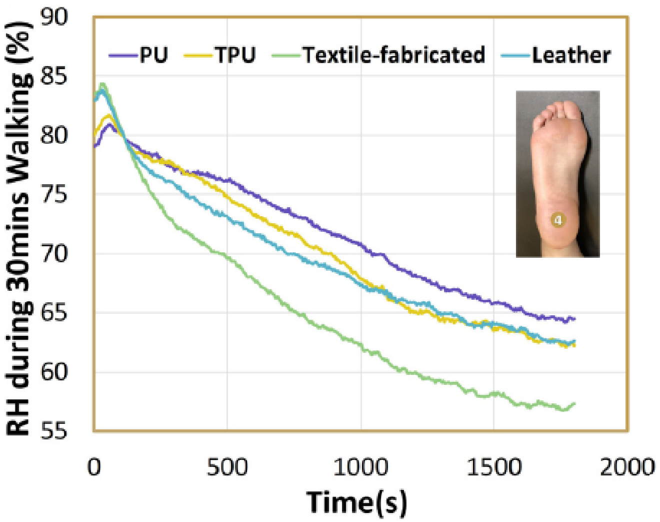
- **Phase 3: Novel Application**

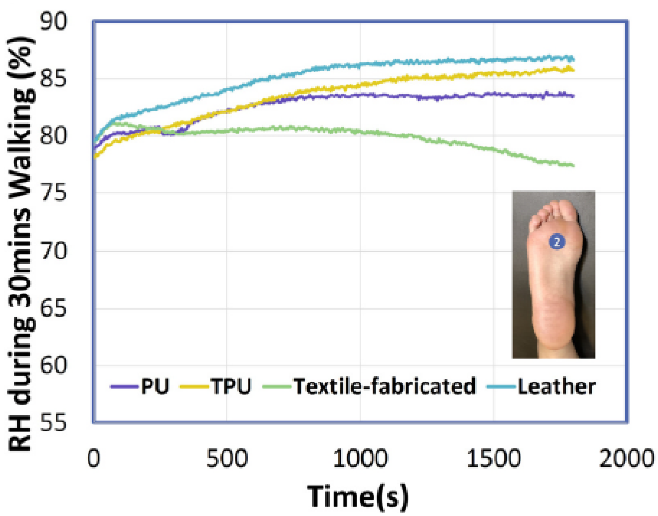


The proposed structure has significantly positive implications for insole applications.



Insole samples of (a) PU, (b) 3D printed TPU, (c) 3D knit with silicone inlay, and (d) leather





The knitted fabric with silicone tube inlay was applied as an insole. While no significant change in skin temperature was observed, there were notable reductions in relative humidity at the sole (3.21%) and heel (24.41%) after 30 minutes of walking.

(refer to https://doi.org/10.1016/j.apergo.2022.103803)

Research Outcomes, Findings & Further Research

- Different inlay methods and materials have been proposed and their effects on fabric properties evaluated.
- Elastic yarn inlaid into the surface layers of spacer fabrics increases thickness, enhances softness, and improves compression energy absorption.
- A linear relationship between the yarn feeding rate of elastic inlay and fabric curvature was observed.
- Silicone inlay enhances flexural rigidity, bending stiffness, compression stiffness, energy absorption, and impact force reduction.
- The tucking pattern of silicone inlay affects surface appearance and roughness. Silicone tube inlay forming tuck stitches on both front and back needle beds further increases thickness and creates a wavy surface corresponding to the tucking pattern.
- Application of the developed fabrics in various products improves air permeability, fit, and moisture transfer.
- Future studies will explore 3D knitted fabric designs and alternative inlay methods, patterns, and materials to optimize fabric properties for diverse end-uses.

Research Dissemination

- **Journal Papers:**
  - Yu, A., Sukigara, S., & Takeuchi, S. (2020). Effect of inlaid elastic yarns and inlay pattern on physical properties and compression behaviour of weft-knitted spacer fabric. Journal of Industrial Textiles, 51(2_suppl), 2688S–2708S. doi: 10.1177/1528083720947740
  - Yu, A., Sukigara, S., Yick, K. L., & Li, P. L. (2020). Novel weft-knitted spacer structure with silicone tube inlay for enhancing mechanical behavior. Mechanics of Advanced Materials and Structures, 29(14), 2053–2064. doi: 10.1080/15376494.2020.1850948
  - Yu, A., Sukigara, S., & Shirakihara, M. (2021). Effect of silicone inlaid materials on reinforcing compressive strength of weft-knitted spacer fabric for cushioning applications. Polymers, 13(21), 3645. doi: 10.3390/polym13213645
  - Li, N. W., Yick, K. L., Yu, A., & Ning, S. (2022). Mechanical and thermal behaviours of weft-knitted spacer fabric structure with inlays for insole applications. Polymers, 14(3), 619. doi: 10.3390/polym14030619
  - Li, N. W., Yick, K. L., & Yu, A. (2022). Novel weft-knitted spacer structure with silicone tube and foam inlays for cushioning insoles. Journal of Industrial Textiles, 51(4_suppl), 6463S–6483S. doi: 10.1177/15280837211073359
  - Yu, A., Sukigara, S., & Yick, K. L. (2022). Curvature control of weft-knitted spacer fabric through elastic inlay. Textile Research Journal, 92(19–20), 3826–3837. doi: 10.1177/00405175221097098
  - Yu, A., Shirakihara, M., Yick, K. L., Sukigara, S., & Chan, K. C. (2022). Development of fully fashioned knitted spacer fabric bra cup: One-step production from yarn. Materials & Design, 219, 110825. doi: 10.1016/j.matdes.2022.110825
  - Ning, K., Yick, K. L., Yu, A., & Yip, J. (2022). Effects of textile-fabricated insole on foot skin temperature and humidity for enhancing footwear thermal comfort. Applied Ergonomics, 104, 103803. doi: 10.1016/j.apergo.2022.103803
  - Kwan, M.-Y., Tu, Y.-F., Yick, K.-L., Yip, J., Li, N. W., Yu, A., & Lo, K.-W. (2024). Enhancing force absorption, stress–strain and thermal properties of weft-knitted inlay spacer fabric structures for apparel applications. Polymers, 16 (21), art. no. 3031. doi: 10.3390/polym162130
  - Le Coz, U., Ringenbach, P., Sakuma, A., & Yu, A. (2024). Flattening behaviour of weft-knitted spacer fabrics. Discover Mechanical Engineering, 3 (1), art. no. 44. doi: 10.1007/s44245-024-00078-z
  - Yu, A., Zhang, Y., & Takeuchi, S. (2025). Advanced design of 3D knitted padding for wearable cushioning in knee protector. Scientific Reports, 15, art. no. 11091. doi: 10.1038/s41598-025-92552-1

Research Dissemination

- **Conference Presentations:**

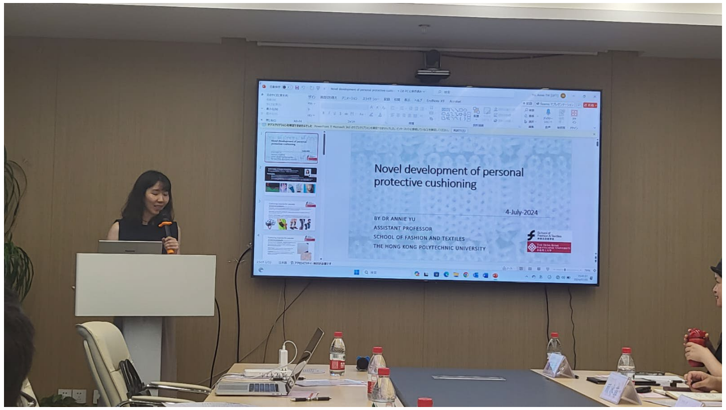
Shirakihara, M., Sukigara, S., & Yu, A., “ホールガーメント横編機による3D形状のブラカップの開発” (Development of 3D-shaped bra cups using a WholeGarment flat knitting machine), The 74th Annual Conference of The Textile Machinery Society of Japan, held online, 27–28 May 2021.

Shu, S. Y., & Yu, A., A novel spacer fabric to reinforce pressure relief for diabetic insole, The 49th Textile Research Symposium, Kyoto Institute of Technology, Kyoto, Japan, 8–9 Oct 2022.

Yu, A., New development in cushioning materials by knitting, 2nd SmartTecStyle Conference, Tiangong University, held online, 20 Dec 2022 (Keynote speaker).

Sasaki, L., Yu, A., & Sukigara, S., “スペーサーファブリックを用いたジョギング用インソールの開発” (Development of jogging insoles using spacer fabric), The 76th Annual Conference of The Textile Machinery Society of Japan, Osaka Science and Technology Center, Osaka, Japan, 1–2 Jun 2023.

Yu, A., Novel development in personal protective cushioning, The Digital & Intelligent Fashion Symposium 2024, Zhejiang Sci-Tech University, China, 5 Jul 2024 (Invited speaker).



Research Dissemination

- **Exhibition - Hokuriku yarn Fair 2023**

- **Award**
  - Kinugasa Textile Award (Academic Category) – Kinugasa Fibre Research Centre

Research Dissemination

- **Invited Speech:**

  Invited Lecture, National Institute of Technology Jalandhar – invited by Dr Kamble, 3D shaped knitted composite for wearable cushioned products, 8 Nov 2022

  Invited Lecture, Kyoto Institute of Technology Center for Fiber and Textile Science (Sengaku Centre) – New development in cushioning materials by knitting, 15 Nov 2022

Dr. B. R. Ambedkar National Institute of Technology Jalandhar
(Institute of National Importance – Under Ministry of Education, Govt. of India)

CERTIFICATE OF APPRECIATION

Conferred upon

Dr. Annie Yu

Assistant Professor, Faculty of Fiber Science and Engineering, Kyoto Institute of Technology, Japan

for Delivering lecture on

"Novel knitted fabrics and functional textiles"

To PhD, Master and Undergraduate students of the Department of Textile Technology, Dr. B. R. Ambedkar National Institute of Technology Jalandhar, India in online mode on 8th November 2022.

Dr. A K Choudhary
Associate Professor and Head, Department of Textile Technology,
Dr B R Ambedkar National Institute of Technology Jalandhar