An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines

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Copyright statement

Preface — My Path towards this Project

My background and experiences are central to my research. They have informed not only my aims and my practice but also my thinking and perspectives as a textile designer. I was educated at Montessori[1] and Steiner[2] schools, both of which emphasised the importance of exploratory, tactile learning in childhood development. Steiner education, in particular, focused on integrating emotional, physical, and spiritual aspects into holistic child development. I became more conscious and active in my interest in materials as a student at Chelsea College of Art and Design and the Royal College of Art. Here, I recognised both the vast opportunities presented by physically engaging with materials and their capacity to transform us, just as we transform them.[3]

I have found textiles to be an inexhaustible medium that offer ways into multiple disciplines and fields of practice. In textiles I found a domain of creative self-expression in which, by gaining technical knowledge and employing skills developed through reflective and embodied experience, I could make a thoughtful contribution to multiple fields of practice. The combination of practice and 'reflection-on-action'[4] set the framework in which I began to recognise the potential of an approach which typically foregrounds sensory engagement and aesthetic appeal alongside the needs of application while offering space for sustainable and ethical considerations.[5] Although my research does not explicitly focus on these values of sustainability or ethics, they are embedded in the same mindset that drives my sensory/aesthetic approach as a textile designer. Through thoughtful engagement with materials I believe we can critically question the hierarchies and dominant structures of knowledge within society and which are reflected in the materials we create and use to shape our world. It is my hope that this body of work goes some way towards supporting this ambition.

Gaining these insights has not, however, been without its challenges. I gained interdisciplinary experience working in a commercial setting in the United States, where I was part of a team developing textiles for performance sport. Here, I recognised opportunities to better integrate material science and textile design into innovative textiles which not only fulfilled functional requirements but were also pleasing from a sensory and aesthetic standpoint. I saw, however, that aspects of my creative training – as well as those of others – were undervalued, misunderstood and considered secondary to both the creative disciplines of industrial and product design and the scientific field. This experience highlighted a gap in my ability to articulate the value of my expertise. This realisation drove my research journey, as I sought to deepen my understanding of how textile design can contribute toward holistic developments in a fast-changing technological landscape.

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[1] Barbara Isaacs, *Understanding the Montessori Approach: Early Years Education in Practice*, [1st ed.] (Routledge, 2012).
[2] Martyn Rawson, *Steiner Waldorf Pedagogy in Schools: A Critical Introduction* (Routledge, 2021).
[3] Don Ihde and Lambros Malafouris, 'Homo Faber Revisited: Postphenomenology and Material Engagement Theory', *Philosophy & Technology*, 32.2 (2019), pp. 195–214, doi:10.1007/s13347-018-0321-7.
[4] Donald A. Schön, *The Reflective Practitioner: How Professionals Think in Action* (Basic Books, 1983).
[5] Rachel Philpott and Faith Kane, 'Textile Thinking': A Flexible, Connective Strategy for Concept Generation and Problem Solving in Interdisciplinary Contexts', in *Craftwork as Problem Solving: Ethnographic Studies of Design and Making*, ed. by J. Marchand and H. Trevor, 1st edn (Routledge, 2016) <https://www.taylorfrancis.com/books/9781134802227> [accessed 17 November 2023].

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A special thank you to my learning support tutor Ray Martin for your ongoing support, to Eleanor Pritchard for helping me to stay accountable through writing support sessions and to Cathy Johns for your support in enhancing the clarity and coherence of this thesis.

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Lastly, but by no means least, thank you to my dearest family and friends for your encouragement and support throughout this journey, I could not have done it without you.

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Abstract

Current research in wearable smart textiles largely resides in ‘hard’ scientific fields, which prioritise technological function, yet often overlook critical design aspects that influence the wearer’s experience. Wearable smart textiles are often viewed merely as flexible platforms for technology, without sufficient consideration of how material interactions impact textile appearance, texture, handle and drape, all of which affect comfort and wearability. This narrow focus limits their potential by neglecting the experiential knowledge necessary for their holistic development. By addressing the gaps that act as barriers to textile designs recognition as a critical discipline in wearable smart textiles, this study explores the ways a textile designer, drawing on their intuitive and hands-on expertise, can advance smart textiles through engagement with the sciences to integrate both technical performance and sensory and tactile experience.

Through reflective experimentation and sampling, textile designers work to harmonise function with sensory and tactile qualities, as articulated by Elaine Igoe. My study draws on Igoe’s thinking to further understand how a ‘soft’, textile design approach can be developed in emerging technology-driven contexts, such as wearable smart textiles. Integrating technology into fabrics, designers like Bruna Goveia da Rocha, Pauline van Dongen, and Emmi Pouta emphasise the material, tactile and experiential qualities of textiles and exemplify this 'soft' textile design approach. However, these design insights usually remain confined to design research, with limited integration into the broader science-led, wearable smart textile field.

A bricolage methodology was chosen for its adaptability, enabling hands-on techniques to be combined with qualitative research. Using a Research through Design (RtD) approach, two exploratory case studies were conducted, focusing on the integration of technological components into knitted and embroidered innersuit samples. These projects involved cutting-edge, science-led contexts, allowing for the practical application of textile design expertise to achieve a balance between experiential qualities and functionality. In the first case study, I acted as a maker, facilitator, and workshop host, contributing textile design to wearable innersuits for nuclear decommissioning operators. In the second, I developed thermoregulation garments for astronauts, conducting semi-structured interviews to gain further insights into the interdisciplinary requirements of smart textile development.

This practice-based research makes contributions across practice, mindset, and methodology. On a practical level, it develops textile design skills to create wearable smart textiles that incorporate polymer optical fibres and fluidic systems, with the aim of balancing function with design. It highlights a shift in approach from traditional to smart textile design, demonstrating how a soft textile approach and sampling can be re-positioned and embedded within wearable smart textiles to create fabrics where experiential qualities, such as appearance, texture, handle and drape, are thoughtfully considered and preserved. The study also fosters a flexible, multidisciplinary approach, in which the designer acts as a ‘material explorer,’ adapting to various roles and contexts. Methodologically, it introduces a ‘soft’ textile design perspective into the smart textile field, bridging the gap between traditional textile design expertise and technological innovation. This reflective, exploratory approach demonstrates both the opportunities and challenges of developing wearable smart textiles when engaging with practitioners from other disciplines.

Word count: 500

Keywords - material innovation, material exploration, smart textiles, interdisciplinary, textile design thinking, practice-based research

Abbreviations

AFFOA - Advanced Functional Fabrics of America
BPT - Biopharmaceutical Tubing
COC-E - Cyclic olefin copolymer-elastomer
E&M interference - Electricity and magnetism interference
EMU - Extravehicular Mobility Unit
EPSRC - Engineering and Physical Sciences Research Council
EVA - Extravehicular Activity
EV - Extravehicular
EVA - Ethylene Vinyl Acetate
ExCG - Exploration cooling garment
FHL - Footfalls and Heartbeats, Ltd.
FPC - Flexible printed circuit
HRV - Heart Rate Variability
HCRS - Helen Hamlyn Centre for Robotic Surgery
ICL - Imperial College London
ID - Internal Diameter
ISS - International Space Station
IUK - Innovate UK
LCVG - Liquid Cooling and Ventilation Garment
LCG - Liquid Cooling Garment
MDS - Material Data Sheet
MRE - Materials Research Exchange
NASA - The National Aeronautics and Space Administration
OD - Outer Diameter
OFS - Optical fibre sensor
PLSS - Portable Life Support System
PMMA - Polymethyl MethAcrylate
POF - Polymer Optical Fibre
PPE - Personal Protective Equipment
PPG - Photoplethysmography
PVC - Polyvinyl Chloride
QMUL - Queen Mary's University, London
RAS - Robotic and Autonomous Systems
RCA - Royal College of Art
RAI - Robotics and AI
RtD - Research through Design
R&D - Research and Development
SBRI - Small Business Research Initiative
S.E.M - Scanning electron microscope
SLCWG - Shortened liquid cooling/warming garment

SNF - Stavros Niarchos Foundation
TPE - Thermoplastic elastomer
TRL - Technology Readiness Level
UKRI - U.K. Research and Innovation
UKRAS Network - UK Robotics and Autonomous Systems Network
UoN OAP - University of Nottingham, Optics and Photonics Group
W - Wall
WCG - Water Cooled Garments

Author’s Declaration

This thesis represents partial submission for the degree of Doctor of Philosophy at the Royal College of Art. I confirm that the work presented here is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

During the period of registered study in which this thesis has been prepared, the author has not been registered for any other academic award or qualification. The material within this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

Signature

Date

Chapter 1. Introduction

1.1. Project Background and Rationale

In this thesis I present a practice-based[6] exploration and contribution to the field of wearable smart textiles. I investigate how a textile designer might advance wearable smart textiles through engagement with the sciences, integrating both technical performance and sensory and tactile experience, and examining the opportunities and challenges of doing so. This applies specifically to a designer who draws on the 'soft,' tacit and embodied knowledge inherent in their discipline.[7] Wearable smart textiles – equipped with capabilities such as biometric measurements, sensing functions, and adaptive responses to bodily stimuli – offer significant potential for non-invasive, personalised monitoring and intervention in fields such as healthcare, occupational safety and sportswear.[8] However, despite advances in technical functionality, critical research gaps remain. These include balancing pertinent functionalities with essential design considerations,[9] such as how material and textile interactions affect appearance, texture, handle and drape – all of which are important for comfort and wearability. In fact, a lack of comfort and wearability is often cited as one of the key reasons why the development and adoption of smart textiles has been slower than initially anticipated.[10]

I frame my research through the language of 'hard' and 'soft', the pairing of which means two different things in this context. First, on a material level, it represents the shift from traditionally 'hard' technologies made of non-textile materials to physically softer materials.[11] Second, these terms can be figuratively deployed to reflect different methodologies and ways of thinking.[12] 'Hard' signifies the quantitative methods and logic prevalent in research into smart textiles and advanced materials; it is

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[6] Linda Candy and Ernest Edmonds, 'Practice-Based Research in the Creative Arts: Foundations and Futures from the Front Line', *Leonardo*, 51.1 (2018), pp. 63–69, doi:10.1162/LEON_a_01471.
[7] Elaine Igoe, *Textile Design Theory in the Making* (Bloomsbury Visual Arts, 2021); Schön, *The Reflective Practitioner*; Michael Polanyi, *The Tacit Dimension* (Doubleday and Co., 1966).
[8] Heitor Luiz Ornaghi Júnior and others, 'Smart Fabric Textiles: Recent Advances and Challenges', *Textiles*, 2.4 (2022), pp. 582–605, doi:10.3390/textiles2040034; Vladan Koncar, *Smart Textiles and Their Applications* (Woodhead Publishing, 2016); Matteo Stoppa and Alessandro Chiolerio, 'Wearable Electronics and Smart Textiles: A Critical Review', *Sensors (Switzerland)*, 14.7 (2014), pp. 11957–92, doi:10.3390/s140711957; Xiaoming Tao, *Handbook of Smart Textiles*, ed. by Xiaomin (Springer Reference, 2015).
[9] Qian Xu, Yabin Yu, and Xiao Yu, 'Analysis of the Technological Convergence in Smart Textiles', *Sustainability*, 14.20 (2022), p. 13451, doi:10.3390/su142013451; Rebecca R. Ruckdashel, Ninad Khadse, and Jay Hoon Park, 'Smart E-Textiles: Overview of Components and Outlook', *Sensors*, 22.16 (2022), p. 6055, doi:10.3390/s22166055; Rebecca R. Ruckdashel, Dhanya Venkataraman, and Jay Hoon Park, 'Smart Textiles: A Toolkit to Fashion the Future', *Journal of Applied Physics*, 129.13 (2021), p. 130903, doi:10.1063/5.0024006; Jane McCann, Richard Hurford, and Adam Martin, 'A Design Process for the Development of Innovative Smart Clothing That Addresses End-User Needs from Technical, Functional, Aesthetic and Cultural View Points.', in *Ninth IEEE International Symposium on Wearable Computers (ISWC'05)* (presented at the Ninth IEEE International Symposium on Wearable Computers (ISWC'05), IEEE, 2005), pp. 70–77, doi:10.1109/ISWC.2005.3.
[10] Jannek Kjøll Sommer, '3 - Why Consumers Resist Wearables and What to Do about It?', in *Smart Clothes and Wearable Technology (Second Edition)*, ed. by Jane McCann and David Bryson, The Textile Institute Book Series (Woodhead Publishing, 2023), pp. 67–80, doi:10.1016/B978-0-12-819526-0.00010-2; Naan Ju and Kyu-Hye Lee, 'Consumer Resistance to Innovation: Smart Clothing', *Fashion and Textiles*, 7.1 (2020), p. 21, doi:10.1186/s40691-020-00210-z.
[11] Cuiqin Fang and others, 'Advanced Design of Fibrous Flexible Actuators for Smart Wearable Applications', *Advanced Fiber Materials*, 6.3 (2024), pp. 622–57, doi:10.1007/s42765-024-00386-9.
[12] Igoe, *Textile Design Theory in the Making*; Pennina Barnett, *Textures of Memory: The Poetics of Cloth*, ed. by Polly Binns and others (Angel Row Gallery, 1999).

predominantly developed within positivist, science-led domains. Such approaches favour fragmented thinking, measurable data, and objective evidence.[13] In contrast, textile design research methods are 'soft' precisely because they rely on tacit, embodied, and experiential knowledge (the intricacies of which are still being explored).[14]

The majority of current research in this field emphasises 'hard', scientific and engineering knowledge frameworks that prioritise technical performance and often overlook aspects of sensory and tactile experience.[15] Consequently, textiles are frequently treated as merely flexible platforms in which to embed technology. This narrow focus, while critical for advancing smart textile functionalities, limits the full potential of textiles by neglecting the 'soft' knowledge necessary for their holistic development. A holistic approach, one that combines technical performance with a sensitivity to how the qualities of materials and textiles can be combined and manipulated to enhance their experiential qualities, is therefore essential to achieve this potential, and to ensure that smart textiles are not only functional but also attuned to the wearer's overall sensory experience.[16] This broader context is closely linked to my own positioning as a practitioner-researcher, which has shaped the approach taken and the knowledge produced throughout this project.

1.1.1. Positioning the practitioner-researcher and practice-based context

As outlined in the preface (see p. 3), this research is shaped by my identity and prior and ongoing experiences as a textile designer working across design education, professional practice and interdisciplinary engagement. My approach to materials, techniques and processes is rooted in hands-on, reflective making and continues to evolve through engagement with science-led teams. This informs both the research aims and objectives and the methods used to generate knowledge.

The research is situated within a practice-based framework, where making, reflection, and the artefact itself are integral to producing new knowledge. While this mode of inquiry is yet to reach a 'settled' status in art and design research literature,[17] practice-based research can be broadly defined as 'an original investigation undertaken in order to gain new knowledge partly by means of practice and the outcomes of that practice.[18]'

A key feature of this practice-based positioning is its reliance on the role of identity in shaping the research process. As design researcher Sebastian Messer argues, practice-based research requires attention to how the practitioner's identity, context, and role intersect with epistemological and methodological

[13] Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Harvard University Press, 1987).
[14] Igoe, *Textile Design Theory in the Making*; Polanyi, *The Tacit Dimension*.
[15] Riikka Townsend, Anne Louise Bang, and Jussi Mikkonen, 'Textile Designer Perspective on Haptic Interface Design: A Sensorial Platform for Conversation Between Discipline', in *Distributed, Ambient and Pervasive Interactions*, ed. by Norbert Streitz and Shin'ichi Konomi, Lecture Notes in Computer Science (Springer International Publishing, 2020), , 110–27 (p. 111), doi:10.1007/978-3-030-50344-4_9.
[16] Jonna Häkkilä, 'Designing for Smart Clothes and Wearables—User Experience Design Perspective', in *Smart Textiles: Fundamentals, Design, and Interaction*, ed. by Stefan Schneegass and Oliver Amft (Springer International Publishing AG, 2017), pp. 259–78 <http://ebookcentral.proquest.com/lib/rcauk/detail.action?docID=4795486> [accessed 13 December 2024].
[17] Candy and Edmonds, 'Practice-Based Research in the Creative Arts', p. 63.
[18] Candy and Edmonds, 'Practice-Based Research in the Creative Arts', p. 63.

choices.[19] My position within the research has shifted in response to disciplinary settings and project stages, reflecting the embedded and negotiated nature of interdisciplinary knowledge production.

These dynamics highlight the multi-faceted and evolving role of identity in practice-based research, as the practitioner-researcher's perspective shifts through ongoing reflective engagement with materials, project partners, and context.[20] This positioning is developed further in Chapter 3, which outlines the methodological frameworks underpinning the research, and revisited in Chapter 6, where I reflect on how engagement with the sciences has contributed to a significant transformation in my identity as a designer. It forms the foundation for the methodological choices, practices, and reflections that follow throughout the thesis.

1.2. Aims and objectives

My research seeks to address the gaps discussed in section 1.1. – which represent significant barriers to the recognition of textile design as a critical discipline in the science-led development of wearable smart textiles – by focusing on the following aims and objectives:

1.2.1. Research aims:

1. To engage in the design and development of wearable smart textiles through interdisciplinary engagement with practitioners from scientific disciplines.
2. To explore the textile designer's role in the evolving field of wearable smart textiles.

1.2.2. Research objectives:

1. Identify textile methods and values that can enhance wearable smart textile design.
2. Examine science-led wearable smart textile research environments to integrate and observe design insights.
3. Critically reflect on the opportunities and challenges for textile designers contributing to the development of wearable smart textile design.
4. Provide a model for the role of practice-based textile design methodologies and mindsets in interdisciplinary projects.

I arrived at my area of focus after an initial hands-on exploration of both smart and advanced materials. This exploration reinforced the value of engaging with the field through experiential knowledge and an embodied approach. It also shifted my perspective away from a purely theoretical engagement (see Appendix A).

In the wearable smart textile domain, I focus on the design of inner-suit samples for applications in extreme environmental conditions. This area represents the cutting edge of material innovation.

[19] Sebastian Messer, 'Documenting Practice Research: Constraints and Opportunities', *Journal of Engineering Design*, 36.3 (2025), pp. 405–38 (p. 405), doi:10.1080/09544828.2024.2427558.
[20] Candy and Edmonds, 'Practice-Based Research in the Creative Arts'; Messer, 'Documenting Practice Research'.

Researchers in this area are also likely to have little prior experience of working with designers, but require input from those with an understanding of textiles designed to be worn on the body. These environments also offer an applied context for applying (a) textile design skills and (b) critical occupational safety and healthcare monitoring. These two major growth areas for wearable smart textiles converge in this context.[21] It is also worth noting that the focus has shifted to include enhancing performance through improving the sensory and tactile aspects of wearable smart textiles[22] because researchers in the 'hard' sciences have already met the challenge of sustaining life in harsh conditions. As a result, scientific institutions and researchers have become more open to incorporating creative approaches in smart textiles designs and development. This, in turn, establishes new forms of engagement across science and textile design.[23] Textile design – with its 'soft' qualities that engender intuitive and affective aesthetic responses – can enhance the sensory and tactile properties of smart textiles.[24] Such insights are necessary if wearable smart textiles are to continue developing beyond niche applications into fabrics that have everyday use (e.g. sportswear).[25]

Here, I focus on material and textile design interactions in smart textiles, specifically through involving the use of smart and functional materials discovered and utilised outside traditional textile design contexts in the last twenty years. Examples include fibre optics and medical-grade polymeric tubing. The context of my research incorporates textiles for use in nuclear decommissioning and space exploration (see Chapters 4 and 5). In each case, the challenges lie in finding an optimal balance between the technical and sensory/aesthetic aspects of the innovative fabrics in question. This is important for increasing (a) the comfort and wearability of these fabrics and (b) their subsequent performance in environments where extreme conditions prevail. Key to achieving this balance is the successful navigation of the different approaches of material science and textile design to thinking and doing, notwithstanding the current lack of guidance for doing so.

1.3. Research on smart textiles and gaps in the field

In the following section, I examine the status of research into smart textiles and highlight the research gaps. Although recent advancements in flexible technologies demonstrate a shift towards 'softness',[26]a critical analysis of studies to date reveals three primary lacunae. These gaps hinder the incorporation of expertise from textile design into the development of wearable smart textiles.

[21] Basel Younes, 'Smart E-Textiles: A Review of Their Aspects and Applications', *Journal of Industrial Textiles*, 53 (2023), p. 15280837231215493, doi:10.1177/15280837231215493; Júnior and others, 'Smart Fabric Textiles'.
[22] Melkie Getnet Tadesse and others, 'Comfort Evaluation of Wearable Functional Textiles', *Materials*, 14.21 (2021), p. 6466, doi:10.3390/ma14216466; Ruckdashel, Venkataraman, and Park, 'Smart Textiles'.
[23] 'Interdisciplinary Textiles SIG', *DRS* <https://www.designresearchsociety.org:443/cpages/textiles-sig> [accessed 23 December 2024].
[24] Elvin Karana and others, 'Alive. Active. Adaptive: Experiential Knowledge and Emerging Materials', *International Journal of Design*, 13.2 (2019), pp. 1–5.
[25] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'.
[26] Vanessa Sanchez, Conor J. Walsh, and Robert J. Wood, 'Textile Technology for Soft Robotic and Autonomous Garments', *Advanced Functional Materials*, 31.6 (2021), p. 2008278, doi:10.1002/adfm.202008278.

First gap. This gap relates to a lack of understanding in science-led wearable smart textile research and development, specifically regarding the role of experiential and embodied knowledge[27] in the process of designing textiles that are tailored to meet nuanced wearer desires.[28] This also relates to (a) the potential integration of such knowledge in advancing smart textiles that are diverse in construction, sensory and tactile aesthetics and (b) anticipating evolving markets and changing consumer values.[29] This gap shows itself in the research literature through the dominance of scientific approaches (which rely heavily on quantitative methodologies) in existing initiatives.[30]

Traditional scientific approaches to knowledge construction and scientific modes of thought are crucial for advancing and characterising robust, new materials and smart components and structures such as sensors, actuators, and transistors.[31] Nonetheless, this first research gap implies that these approaches are limited in their ability to advance smart textiles' sensory and aesthetic qualities because quantitative methodologies do not account for the importance of embodied knowledge and reflective practice in the creative process. However, these elements are crucial for developing textiles that are functional, pleasing from a sensory perspective, and requisite for the needs of the 'human body and society.'[32] These considerations are, however, inherent in the creative practices of textile designers, who harness them as essential factors to inform how a material 'looks' or 'feels'.[33] By integrating cultural, material, and conceptual factors into their work,[34] they create textiles that resonate on multiple levels. Through intuitive insight, they influence our sensory and aesthetic impressions, ultimately enriching the products.[35] This can in turn transform textiles into both meaningful and active participants in our lives.[36]

[27] Michael Polanyi, *Personal Knowledge: Towards a Post-Critical Philosophy* (Routledge, 1997); Camilla Groth and others, 'Conditions for Experiential Knowledge Exchange in Collaborative Research across the Sciences and Creative Practice', *CoDesign*, 16.4 (2020), pp. 328–44, doi:10.1080/15710882.2020.1821713; Martijn ten Bhömer, 'Designing Embodied Smart Textile Services: The Role of Prototypes for Project, Community and Stakeholders', 2016 <https://www.academia.edu/25892282/Designing_embodied_smart_textile_services_The_role_of_prototypes_for_project_community_and_stakeholders> [accessed 3 November 2023].

[28] Elaine Igoe, 'In Textasis: Matrixial Narratives of Textile Design' (Royal College of Art, 2013); Rachel Philpott, 'Entwined Approaches: Integrating Design, Art and Science in Design Research-by-Practice', *Design Research Society Conference*, 2012, p. 16.

[29] Karana and others, 'Alive. Active. Adaptive: Experiential Knowledge and Emerging Materials'.

[30] Gizem Acar, Ozberk Ozturk, and Murat Kaya Yapici, 'Wearable Graphene Nanotextile Embedded Smart Armband for Cardiac Monitoring', in *2018 IEEE SENSORS* (presented at the 2018 IEEE Sensors, IEEE, 2018), pp. 1–4, doi:10.1109/ICSENS.2018.8589800; Jaehong Lee and others, 'Conductive Fiber‐Based Ultrasensitive Textile Pressure Sensor for Wearable Electronics', *Advanced Materials*, 27.15 (2015), pp. 2433–39, doi:10.1002/adma.201500009; Dongzhan Chen and others, 'A Smart Scarf for Pulse Signal Monitoring Using a Flexible Pressure Nanosensor', in *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program* (presented at the UbiComp '14: The 2014 ACM Conference on Ubiquitous Computing, ACM, 2014), pp. 237–42, doi:10.1145/2641248.2666714; Thomas Loher and others, 'Stretchable Electronic Systems for Wearable and Textile Applications', in *2008 IEEE 9th VLSI Packaging Workshop of Japan* (presented at the 2008 IEEE 9th VLSI Packaging Workshop of Japan, IEEE, 2008), pp. 9–12, doi:10.1109/VPWJ.2008.4762190.

[31] Isabelle Stengers, *Cosmopolitics*, Posthumanities, 9–10 (University of Minnesota Press, 2010); Isabelle Stengers, *Cosmopolitics II*, *Choice Reviews Online* (University of Minnesota Press, 2012), xlix, doi:10.5860/choice.49-5024; Leema K. Berland, 'Explaining Variation in How Classroom Communities Adapt the Practice of Scientific Argumentation', *Journal of the Learning Sciences*, 20.4 (2011), pp. 625–64, doi:10.1080/10508406.2011.591718.

[32] Tiago M. Fernández-Caramés and Paula Fraga-Lamas, 'Towards The Internet of Smart Clothing: A Review on IoT Wearables and Garments for Creating Intelligent Connected E-Textiles', *Electronics*, 7.12 (2018), p. 405, doi:10.3390/electronics7120405.

[33] Igoe, 'In Textasis: Matrixial Narratives of Textile Design'.

[34] Colin Gale and Jasbir Kaur, *The Textile Book* (Berg, 2002), pp. 37–39; Claire Lerpiniere, 'Value Definition in Sustainable (Textiles) Production and Consumption', 2020, pp. 85–107, doi:10.1007/978-3-030-37035-0_5.

[35] Lerpiniere, 'Value Definition in Sustainable (Textiles) Production and Consumption'.

[36] Matilda McQuaid, 'Curating Extreme Textiles, Designing for High Performance', in *The Handbook of Textile Culture*, ed. by Janis Jefferies, Diana Wood Conroy, and Hazel Clark, Paperback edition (Bloomsbury Visual Arts, 2016), p. 276.

Second gap. The most widely cited papers reviewing smart textiles do not acknowledge, and in fact largely overlook, the role and contribution of textile design in the developing field,[37] despite the fact there is a well-established (albeit niche) community of textile-based practitioner-researcher initiatives.[38] These include Satomi and Perner-Wilson's Kobakant,[39] the E-Textiles Summer camp,[40] and fashion labels like Studio XO,[41] CuteCircuit, [42]and others.[43] These initiatives have played an important role in the development of the field, particularly in terms of exploring open approaches to knowledge-sharing and the potential of sensory experiences it offers. Arguably, this lack of understanding prevents the field from harnessing the inherent ability of textile designers to (a) select and design market- and product-appropriate materials and structures and (b) create textiles that both perform technically and appeal on sensory and tactile levels.

Part of the challenge related to this is that textile design research is a relatively emerging field, one that is marked by a specific blend of design knowledge[44] that tends to remain tacit. Historical biases, the problematic perceived image of fashion and textiles,[45] and the feminine-gendered nature of the craft[46] can prevent textile design from being regarded as a rigorous academic field. This marginalisation poses a challenge for bridging the 'sensory gap[47]' in wearable smart textiles because the knowledge in the discipline is still being articulated.

Third gap. A holistic approach necessitates integration across multiple disciplines and considerations beyond merely technological and commercial factors. The third gap I have identified concerns a lack of guidance for interdisciplinary engagement in the field.[48] Despite a shared research interest in exploring smart textile concepts, scholars often operate in silos (i.e they follow their own specialist methods).[49] This could be addressed in two key areas:

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[37] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'; Wei Weng and others, 'Smart Electronic Textiles', *Angewandte Chemie International Edition*, 55.21 (2016), pp. 6140–69, doi:10.1002/anie.201507333; Stoppa and Chiolerio, 'Wearable Electronics and Smart Textiles: A Critical Review'; Kunigunde Cherenack and Liesbeth Van Pieterson, 'Smart Textiles: Challenges and Opportunities', *Journal of Applied Physics*, 112.9 (2012), p. 091301, doi:10.1063/1.4742728.
[38] Irene Posch and Geraldine Fitzpatrick, 'The Matter of Tools: Designing, Using and Reflecting on New Tools for Emerging eTextile Craft Practices', *ACM Transactions on Computer-Human Interaction*, 28.1 (2021), pp. 1–38, doi:10.1145/3426776; Leah Buechley and Hannah Perner-Wilson, 'Crafting Technology: Reimagining the Processes, Materials, and Cultures of Electronics', *ACM Transactions on Computer-Human Interaction*, 19.3 (2012), pp. 1–21, doi:10.1145/2362364.2362369.
[39] Kobekant, 'HOW TO GET WHAT YOU WANT' <https://www.kobakant.at/DIY/> [accessed 5 November 2023].
[40] Anja Hertenberger and others, '2013 E-Textile Swatchbook Exchange: The Importance of Sharing Physical Work', in *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program* (presented at the UbiComp '14: The 2014 ACM Conference on Ubiquitous Computing, ACM, 2014), pp. 77–81, doi:10.1145/2641248.2641276.
[41] Sibel Deren Guler, Madeline Gannon, and Kate Sicchio, *Crafting Wearables: Blending Technology with Fashion* (Apress, 2016), p. 167.
[42] 'CUTECIRCUIT | CuteCircuit Wearable Technology' <https://cutecircuit.com/> [accessed 5 November 2023].
[43] Sabine Seymour, *Fashionable Technology: The Intersection of Design, Fashion, Science, and Technology* (Springer, 2008).
[44] Igoe, 'In Textasis: Matrixial Narratives of Textile Design', p. 73.
[45] Efrat Tseëlon, *Masquerade and Identities: Essays on Gender, Sexuality and Marginality* (Routledge, 2001).
[46] Igoe, *Textile Design Theory in the Making*.
[47]Amy Winters, 'Why Does Soft Matter? Exploring the Design Space of Soft Robotic Materials and Programmable Machines' (Royal College of Art, 2017).
[48] Janet Coulter, 'The Designers Leap: Boundary Jumping to Foster Interdisciplinarity between Textile Design and Science', *Journal of Textile Design Research and Practice*, 6.2 (2018), pp. 137–62, doi:10.1080/20511787.2018.1451211.
[49] Ruckdashel, Khadse, and Park, 'Smart E-Textiles', p. 11.

1. Through calls for greater understanding related to (a) contrasting work processes and conceptual frameworks and (b) the need to develop new design methodologies.[50]
2. Interdisciplinary textile research, where there is an emphasis on the need for (a) improved communication channels between disciplines[51] and (b) the creation of the smart textiles field's first interdisciplinary journal.[52]

My thesis attempts to bridge the divide between 'hard' and 'soft' knowledge in practice by bringing textile designers' sensory/aesthetic, experiential, and embodied expertise to bear on the smart textile landscape. I shall also demonstrate how interdisciplinary working can enhance smart textile design (both in the present and the future).

1.4. Methodology and practice

To address my aims and objectives, I employed an overarching bricolage approach owing to its flexibility in combining practical, hands-on techniques with qualitative research. I utilised a Research through Design (RtD) approach in the context of two exploratory case studies. This 'soft' textile design approach allowed me to employ a number of visual and embodied hands-on and craft-based design methods for data collection and analysis, including textile sampling (e.g., knitting and embroidery) and 'visual thinking' (i.e., sketching and diagramming). My exploratory case studies include a combination of contextual review (comprising literature and practice reviews), semi-structured interviews, and workshops. These exploratory case studies were situated within science-led research contexts, which focused on the design and development of wearable inner-suits with integrated technologies intended for nuclear decommissioning operators (Chapter 4) and astronauts (Chapter 5). The goal was to demonstrate the integration of scientific innovations and textile design. This combination allows me to bring textile designs' 'soft', experiential knowledge of textile design into contact with technology. This methodological approach is situated within the practice-based positioning outlined above in Section 1.1.1, where the act of making and the multifaceted identity of the researcher-practitioner are central to knowledge generation.[53]

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[50] Emmi Pouta, 'Layered Approaches - Woven eTextile Explorations Through Applied Textile Thinking', 2023 <https://research.aalto.fi/en/publications/layered-approaches-woven-etextile-explorations-through-applied-te> [accessed 3 November 2023]; Lucie Hernandez, 'Introducing a Framework for Crafting E-Textiles: Exploring a Material Investigation into Technology', *Journal of Textile Design Research and Practice*, 10.1 (2022), pp. 39–58, doi:10.1080/20511787.2021.1994207; Riikka Claire Townsend and others, 'The Cross-Section of a Multi-Disciplinary Project in View of Smart Textile Design Practice', *Journal of Textile Design Research and Practice*, 5.2 (2017), pp. 175–207, doi:10.1080/20511787.2018.1449076; Sarah Walker and others, 'Facilitating Participatory Practice for Smart Textiles', in *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers - UbiComp '15* (presented at the the 2015 ACM International Joint Conference, ACM Press, 2015), pp. 521–26, doi:10.1145/2800835.2801658.

[51] Sarah Wilkes and others, 'Design Tools for Interdisciplinary Translation of Material Experiences', *Materials and Design*, 90 (2014), pp. 1228–37, doi:10.1016/j.matdes.2015.04.013; Rosie Hornbuckle, 'Materials Liaisons: Facilitating Communication in Design-Driven Material Innovation (DDMI) Projects', in *DRS2018: Catalyst* (Design Research Society, 2018), iv, doi:10.21606/drs.2018.446; Tunde Kirstein, *Multidisciplinary Know-How for Smart-Textiles Developers* (The Textile Institute, Woodhead Publishing in Textiles: Number 139, 2013).

[52] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'.

[53] Candy and Edmonds, 'Practice-Based Research in the Creative Arts'; Messer, 'Documenting Practice Research'.

During my research, I positioned myself as a maker and 'material explorer'. This 'practitioner-researcher identity' supported me to flexibly navigate my exploratory case studies:

1. First as a maker, enabler, and facilitator, hosting a workshop for developing wearable textiles for nuclear decommissioning operators.
2. Second as both a maker, developing wearable thermoregulation garments for astronauts, and a researcher gathering additional insights through qualitative, semi-structured interviews.

As discussed in greater detail in the methodology chapter, my research is notably underpinned by theoretical perspectives found in textile design research. Both case studies were designed to support me in addressing my aims and objectives by allowing me to obtain first-hand experience and understanding of how soft, textile-design-based approaches can contribute to the design of wearable smart textiles.

In the first case study—'Making photonic textiles'—I aimed to (a) explore the technological landscape of smart textiles and (b) embed textile design skills and approaches into the 'hard' challenge-driven context of nuclear decommissioning, and (c) reflect on their value therein. In addition, I also wished to investigate the position of textile design and the designer's role in what I hoped would be a highly interdisciplinary smart textile domain. This involved working closely with photonics and electronics engineers.

I aimed to create textiles that exhibited positive design attributes, such as an appealing handle, texture and appearance, rather than mere functionality. My aims were driven by two key beliefs:

1. Tacit textile knowledge – the knowledge that is implicit in our patterns of action and our haptic engagement with the materials with which we work[54]– can benefit the development of smart textiles.
2. The process of textile sampling can enable one to 'think through' their making.[55]

In the second of my two case studies, 'Designing textiles for integrated networks of fluidic heating and cooling for astronauts' inner-suits', my primary objective was to entwine 'soft' textile design knowledge with the advanced requirements of astronauts' thermoregulatory garments. I also built on insights gained from the shortcomings of interdisciplinarity observed in the first case study (see 4.3.4.1), I then embarked on a six-month embedded residency within the Future AI and Robotics for Space (FAIR-SPACE) team at the Hamlyn Centre for Robotic Surgery (HCRS), Imperial College London (ICL). This immersion was strategic. It allowed me to understand the FAIR-SPACE team's challenges from a first-hand perspective prior to proposing a fully interdisciplinary, textile-based solution – a solution that would infuse the design brief with greater conceptual input than had been possible in the previous study.

Throughout my research, I worked with previously unfamiliar smart and functional materials – materials that had been synthesised within scientific and engineering frameworks. These materials

[54] Schön, *The Reflective Practitioner*, p. 49.
[55] Tim Ingold, *Making: Anthropology, Archaeology, Art and Architecture* (Routledge, 2013).

included polymer optical fibres and medical-grade polymeric fibres and tubing. Each of my case studies emerged from attempts to improve the comfort and wearability of innovations in wearable smart textiles and thus advance their development. By bringing these innovations closer to their intended applications, I sought to demonstrate their feasibility and proof-of-concept. Each study involved engagement with researchers working in scientific and engineering disciplines. The case studies therefore presented different challenges, for which I had to find different ways of navigating my position as a textile designer or 'material explorer'.

Practice was central to my research, and it served two main purposes:

1. Creating tangible textile samples allowed me to use my expertise in trying to meet the requirements for each wearable smart textile.
2. This in turn, enabled me to construct both the knowledge and understanding required to address my aims and objectives (1.2).

In both case studies, my role as maker was central to my engagement with scientific teams working on smart textiles. Being a maker facilitated my entry into the field and helped me to achieve my specific goals for each study. I combined different learning modes, including practical know-how and theoretical knowledge, to create samples using integrated polymer optical fibres (Appendix G) and networks of polymeric tubing (Appendix Q). A key similarity between the case studies here lies in their similarity in terms of approach – knitted textiles – which I used in order to enhance my understanding of materials and processes.[56] However, I also explored embroidery and mixed media techniques.

1.5. Main research findings

My central findings are:

1. The complexities of interdisciplinary engagement and how they shaped the evolving role of the textile designer within science-led smart textile contexts.
2. The need for a fluid mindset to bridge technical and creative domains.
3. The value of integrating tacit, experiential knowledge to enhance comfort, wearability and sensory appeal.

A significant insight of this research has been that the very journey taken in my research had transformative effects on my practice, thinking and sense of self as a practitioner.

[56] Kristina Niedderer, 'Mapping the Meaning of Knowledge in Design Research', *Design Research Quarterly 2*, 2, 2007, pp. 1 & 5–13; David A. Kolb, *Experiential Learning: Experience as the Source of Learning and Development* (Prentice-Hall, 1984).

1.6. Research significance and contribution

I have outlined the gaps that my research seeks to address. It is important to note, however, that my study goes beyond merely addressing these gaps. Indeed, the need for interdisciplinarity in smart textile research is about more than harnessing the commercial advantages to be gained through integrating both sensory and technical perspectives. I hope to demonstrate that our interactions with materials have a transformative potential. A material's capacity to affect how we feel is informed by its historical and contemporary usage and may influence us in ways that we have not foreseen, ultimately impacting that textile's performance. Because textiles can dramatically alter our lives, they must be developed using an interdisciplinary blend, one that encompasses many aspects of our experience. The dream is that this can be achieved through the 'full utilisation of the textile designer's intellectual capital.'[57]A textile designer's expertise is often rooted in aesthetic and craft-based values.[58] To better manage what textile designers have to offer, we must expand our understanding of how they can contribute and develop their expertise in novel contexts. Doing so would offer us new examples of textile design research, which can, in turn, be applied to smart textiles.

My research contributions build on work by textile theorists, such as Claire Pajazkcowska[59] and Elaine Igoe[60], who have articulated textile designers' specific expertise. Marion Lean,[61] has, in turn, situated her approach to textile design within multidisciplinary settings (e.g. data policy departments). In a sense, my research moves beyond current research in its focus on the making process itself, an analysis of what I am making, and a study of the development of my role within a multidisciplinary team incorporating both scientific and design-based skills. The thesis therefore contributes to textile design research by focusing on both the practice of making within previously uncharted scientific fields and the application of 'soft' textile design knowledge to the wearable smart textile domain.

In more specific terms, my research makes three distinct and original contributions in terms of the *practice, mindset,* and *methodology* of textile design:

1. Practical methods for integrating and securing polymer optical fibres and networks of fluidic systems in wearable smart textiles.
2. A shift in designer identity from textile designer to smart textiles designer, emphasising adaptability within interdisciplinary contexts.
3. Methodological insights into the value of 'soft' textile design approaches in science-driven fields.

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[57] Lerpiniere, 'Value Definition in Sustainable (Textiles) Production and Consumption', p. 85.
[58] Louise Valentine and others, 'Design Thinking for Textiles: Let's Make It Meaningful', *Design Journal*, 20.sup1 (2017), pp. S964–76, doi:10.1080/14606925.2017.1353041.
[59] Claire Pajaczkowska, 'Making Known: Psychoanalysis and the Nine Types of Textile Thinking', in *The Handbook of Textile Culture*, ed. by Janis Jefferies (Bloomsbury, 2016), pp. 79–94.
[60] Igoe, *Textile Design Theory in the Making*.
[61] Marion H A Lean, 'Materialising Data Experience Through Textile Thinking' (Royal College of Art and Design, 2020) <https://search.proquest.com/docview/2440369175?accountid=31533%0Ahttps://researchonline.rca.ac.uk/4443/>.

These contributions highlight how *making* within scientific fields advances our knowledge and understanding of the expertise that textile design can bring to bear in other disciplines.

Chapter 2. Literature review

2.1. Introduction and background

In identifying this research project's unique contributions to textile design research and theory, two main areas warrant comprehensive review:

1. Recent advancements in wearable smart textiles. This can help engender a good understanding of the technical context in the research field in which my thesis is positioned.
2. The contemporary landscape of textile design research approaches and practices. This can help to create an appreciation of the theoretical and methodological underpinnings of the 'soft' textile design approach I adopt in this research study—an approach that emphasises sensory, tactile and embodied qualities.

In reviewing these areas, I shall emphasise the limitations associated with developing innovative textiles from a single perspective and highlight the research gaps this thesis seeks to fill (Section 1.3).

In what follows, I shall critically assess the existing literature and highlight pertinent intersections and disparities between textile design and scientific research. To conclude, I identify key areas in which original contributions to knowledge may be made within the broader field.

2.1.1. Wearable smart textiles

The 'smart clothing'[62] phenomenon, which has emerged from innovations in smart textiles demands the merging of science and technology with art and design and requires input from technical, functional, aesthetic and cultural viewpoints[63] to produce the necessary appealing tactile and visual aesthetics, as well as functions for increased performance.[64] Despite this, the field continues to sit predominantly within the sciences, the current landscape of which is primarily focused on quantifiable functionality, such as sensing, data collection and performance metrics.

Smart textiles lie at the forefront of materials science evolution and are attracting considerable attention. Offering a broad definition, Xiaoming Tao, Director of the Research Institute for Intelligent Wearable Systems at Hong Kong Polytechnic, describes smart textiles as 'materials and structures that sense and react to environmental conditions or stimuli, such as those from mechanical, thermal, chemical,

[62] Chi-Wai Kan and Yin-Ling Lam, 'Future Trend in Wearable Electronics in the Textile Industry', *Applied Sciences*, 11.9 (2021), p. 3914, doi:10.3390/app11093914.
[63] McCann, Hurford, and Martin, 'A Design Process for the Development of Innovative Smart Clothing That Addresses End-User Needs from Technical, Functional, Aesthetic and Cultural View Points.'
[64] Sarah Elizabeth Braddock Clarke, 'Clothing+embedded Technology: Past Challenges, Future Opportunities', in *Smart Clothes and Wearable Technology (Second Edition)*, ed. by Jane McCann and David Bryson, The Textile Institute Book Series (Woodhead Publishing, 2023), pp. 3–37, doi:10.1016/B978-0-12-819526-0.00007-2.

electrical, magnetic or other sources.'[65] Van Langenhove and colleagues have offered a more detailed perspective. They focus on reaction mechanisms, noting that these may manifest as intrinsic material properties, such as a colour change, or more complex processes that are actively steered by embedded electronics.[66]

Older wearable technologies often feature bulky components to facilitate data collection in items such as footwear. Smart textiles, in contrast, benefit from technological advances, particularly in nanoscience and technology, that have made key components (e.g. sensors, actuators, power sources and wireless communication systems) smaller and more flexible.[67] Thus, when incorporating traditionally rigid elements (e.g. electronic circuits in fabrics), textile's design allows the materials to become part of a system that is both malleable and soft by virtue of its structural design, which enhances the practicality and comfort of smart textiles that are intended to be worn on the body while positioning them as the next generation of high-tech products.[68]

Smart functions, (such as electronic, thermal or absorption properties) can also be integrated at the yarn and fibre level, whether this is via shape-changing yarns,[69] an inherent material property or a surface coating or treatment.[70] In this context, electrical conductivity, for instance, might be obtained by either drawing fibres from conductive metals or polymers or by spiralling a fibre core with conductive ribbons or metal threads.[71] Phase change materials and optical fibres are used in addition to electronics.[72] As depicted in Figure 2.1, these functions can then be incorporated into or onto textiles using a range of

[65] Xiaoming Tao, *Smart Fibres, Fabrics and Clothing*, ed. by Textile Institute (Manchester, England) and Xiaoming Tao, Woodhead Publishing Limited Series on Fibres (CRC Press ; Woodhead Pub, 2001), pp. 2–3.
[66] Lieva van Langenhove, *Smart Textiles for Medicine and Healthcare: Materials, Systems and Applications*, ed. by Lieva van Langenhove, Woodhead Publishing in Textiles, 1. publ (CRC Press, 2007).
[67] Chang Peng and others, 'Recent Advances of Soft Actuators in Smart Wearable Electronic-Textile', *Advanced Materials Technologies*, 9.15 (2024), p. 2400079, doi:10.1002/admt.202400079; Zirong Luo and others, 'Knitting Elastic Conductive Fibers of MXene/Natural Rubber for Multifunctional Wearable Sensors', *Polymers*, 16.13 (2024), p. 1824, doi:10.3390/polym16131824; Zhe Yan and others, 'Recent Advances in Flexible Wearable Supercapacitors: Properties, Fabrication, and Applications', *Advanced Science*, 11.8 (2024), p. 2302172, doi:10.1002/advs.202302172.
[68] Yitao Zhao and others, 'Recent Advances in Flexible Wearable Technology: From Textile Fibers to Devices', *The Chemical Record*, 24.3 (2024), p. e202300361, doi:10.1002/tcr.202300361; Junli Chen and others, 'Review of Textile-Based Wearable Electronics: From the Structure of the Multi-Level Hierarchy Textiles', *Nano Energy*, 117 (2023), p. 108898, doi:10.1016/j.nanoen.2023.108898; Younes, 'Smart E-Textiles'.
[69] Sanchez, Walsh, and Wood, 'Textile Technology for Soft Robotic and Autonomous Garments'; Carter S. Haines and others, 'Artificial Muscles from Fishing Line and Sewing Thread', *Science*, 343.6173 (2014), pp. 868–72, doi:10.1126/science.1246906.
[70] Valentin Gaubert and others, 'Enhancing Electrical and Mechanical Properties of Conductive Textile for Wearable Embedded Systems Through Copper Electroplating', *Advanced Engineering Materials*, 26.5 (2024), p. 2301436, doi:10.1002/adem.202301436; Jidong Shi and others, 'Smart Textile‐Integrated Microelectronic Systems for Wearable Applications', *Advanced Materials*, 32.5 (2020), p. 1901958, doi:10.1002/adma.201901958; Anja Lund and others, 'Electrically Conducting Fibres for E-Textiles: An Open Playground for Conjugated Polymers and Carbon Nanomaterials', *Materials Science and Engineering R: Reports*, 126.January (2018), pp. 1–29, doi:10.1016/j.mser.2018.03.001; Eric Devaux and others, 'Processing and Characterization of Conductive Yarns by Coating or Bulk Treatment for Smart Textile Applications', *Transactions of the Institute of Measurement and Control*, 29.3–4 (2007), pp. 355–76, doi:10.1177/0142331207081726.
[71] Zhe Yin and others, 'Electronic Fibers/Textiles for Health‐Monitoring: Fabrication and Application', *Advanced Materials Technologies*, 8.3 (2023), p. 2200654, doi:10.1002/admt.202200654; Theodore Hughes-Riley, Tilak Dias, and Colin Cork, 'A Historical Review of the Development of Electronic Textiles', *Fibers*, 6.2 (2018), p. 34, doi:10.3390/fib6020034; C.R. Cork, 'Conductive Fibres for Electronic Textiles', in *Electronic Textiles* (Elsevier, 2015), pp. 3–20, doi:10.1016/B978-0-08-100201-8.00002-3; Tilak Dias, *Electronic Textiles: Smart Fabrics and Wearable Technology* (Elsevier, 2015).
[72] A Schwarz-Pfeiffer and others, 'Smarten up Garments through Knitting', *IOP Conference Series: Materials Science and Engineering*, 141 (2016), p. 012008, doi:10.1088/1757-899X/141/1/012008.

traditional textile techniques, including knitting[73] (Figure 2.1a), weaving[74] (Figure 2.1b), sewing[75] (Figure 2.1c), embroidery[76] (Figure 2.1d) and screen and inkjet printing[77] (Figure 2.1e).

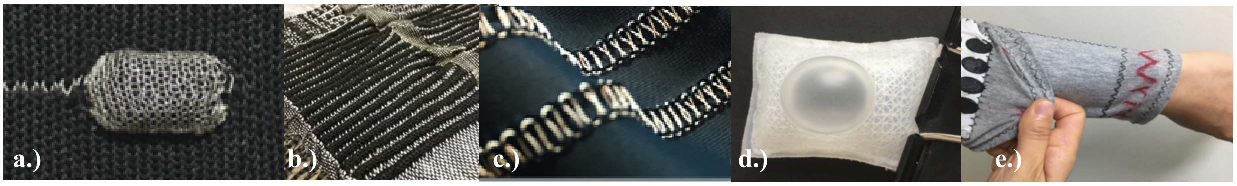

Figure 2.1. *Additive and constructed textile techniques utilised in smart textiles: a) Pressure sensor knitted in conductive yarn. In: Jifei Ou and others, 'SensorKnit: Architecting Textile Sensors with Machine Knitting', 3D Printing and Additive Manufacturing, 6.1 (2019), pp. 1–11, doi:10.1089/3dp.2018.0122 p.6). b) Woven sample for sensing headband. In: Laura Devendorf and others, 'Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency', in Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, CHI '20 (ACM, 2020), pp. 1–13, doi:10.1145/3313831.3376820 p.7). c) Stretchable conductive signal lines fabricated using overlock stitching methods. In: Yichu Jin and others, 'Soft Sensing Shirt for Shoulder Kinematics Estimation', in 2020 IEEE International Conference on Robotics and Automation (ICRA), (IEEE, 2020), pp. 4863–69, doi:10.1109/ICRA40945.2020.9196586 (p. 4864). d) Machine-embroidered inflatable actuator. In: Bruna Goveia da Rocha, and others, 'Embroidered Inflatables: Exploring Sample Making in Research through Design', Journal of Textile Design Research and Practice, 9.1 (2021), pp. 62–86, doi:10.1080/20511787.2021.1885586, p.1). e) Screen printed electrode array (in: Kai Yang and others, p.8).*

[73] Jifei Ou and others, 'SensorKnit: Architecting Textile Sensors with Machine Knitting', *3D Printing and Additive Manufacturing*, 6.1 (2019), pp. 1–11, doi:10.1089/3dp.2018.0122; Amy Chen and others, 'Challenges in Knitted E-Textiles', in *Advances in Intelligent Systems and Computing*, ed. by Jiating Zhu and others (Springer International Publishing, 2019), dcccxlix, 129–35, doi:10.1007/978-3-319-99695-0_16; Akio Sakaguchi and others, 'Fabrication of Optical Fiber Embedded Knitted Fabrics for Smart Textiles', *Journal of Textile Engineering*, 62.6 (2016), pp. 129–34, doi:10.4188/jte.62.129; Linda Oscarsson and others, 'Flat Knitting of a Light Emitting Textile with Optical Fibres', *Autex Research Journal*, 9.2 (2009), pp. 61–65.

[74] Laura Devendorf and others, 'Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency', in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20 (Association for Computing Machinery, 2020), pp. 1–13, doi:10.1145/3313831.3376820; Pouta, 'Layered Approaches - Woven eTextile Explorations Through Applied Textile Thinking'; Ivan Poupyrev and others, 'Project Jacquard: Interactive Digital Textiles at Scale', *Conference on Human Factors in Computing Systems - Proceedings*, 2016, pp. 4216–27, doi:10.1145/2858036.2858176; Lynn Tandler, 'The Role of Weaving in Smart Material Systems', ぎょうせい (University of Northumbria at Newcastle, 2016); Jussi Mikkonen and Emmi Pouta, 'Weaving Electronic Circuit into Two-Layer Fabric', in *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers - UbiComp '15* (presented at the the 2015 ACM International Joint Conference, ACM Press, 2015), pp. 245–48, doi:10.1145/2800835.2800936.

[75] Yichu Jin and others, 'Soft Sensing Shirt for Shoulder Kinematics Estimation', in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 2020, pp. 4863–69, doi:10.1109/ICRA40945.2020.9196586.

[76] Bruna Goveia da Rocha and others, 'Embroidered Inflatables: Exploring Sample Making in Research through Design', *Journal of Textile Design Research and Practice*, 9.1 (2021), pp. 62–86, doi:10.1080/20511787.2021.1885586; Bruna Goveia Da Rocha and others, 'Inflatable Actuators Based on Machine Embroidery' (presented at the Textile Intersections, Loughborough University, 2019), doi:10.17028/RD.LBORO.9724688.V1.

[77] Kai Yang and others, 'Development of User-Friendly Wearable Electronic Textiles for Healthcare Applications', *Sensors (Switzerland)*, 18.8 (2018), pp. 1–13, doi:10.3390/s18082410; Isidoro Ibanez Labiano and others, 'Screen Printing Carbon Nanotubes Textiles Antennas for Smart Wearables', *Sensors*, 21.14 (2021), p. 4934, doi:10.3390/s21144934.

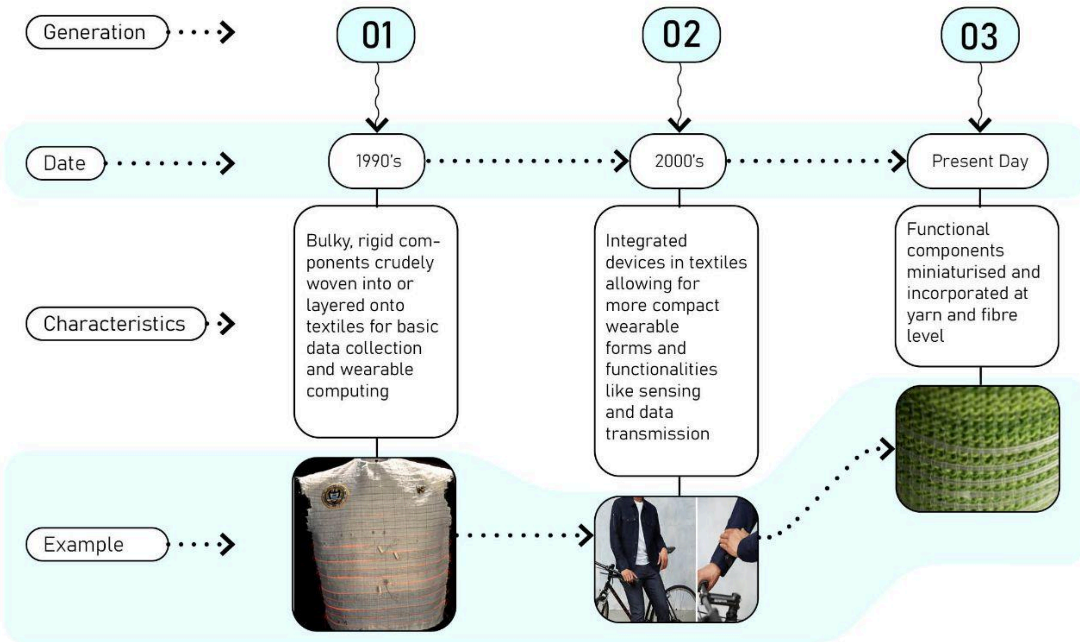

Figure 2.2. *Visual timeline of smart textile evolution over three generations.*

Figure 2.2. illustrates a visual timeline of the transformation of smart textiles' from rigid components to flexible, programmed, active textile systems,[78] over the past thirty years and highlights the evolution of smart textiles through three generations:

1. Rigid electronics in a textile platform, illustrated with the wearable motherboard (Generation 1).[79]
2. Devices embedded in textiles: the Levi's Commuter Trucker Jacket (Generation 2).[80]
3. Fully textile-based devices, illustrated by a digital fibre technology developed at MIT (Generation 3).[81]

Based on the generational framework described by leading researchers in the field,[82] Figure 2.2 illustrates how technical advances have paved the way for developments that are more flexible and more lightweight, that are better suited to more seamless integration into wearable smart textiles. The textile industry is therefore expanding beyond its traditional scope and into more sophisticated applications. The

[78] Sanchez, Walsh, and Wood, 'Textile Technology for Soft Robotic and Autonomous Garments'.
[79] C. Gopalsamy and others, 'The Wearable Motherboard™: The First Generation of Adaptive and Responsive Textile Structures (ARTS) for Medical Applications', *Virtual Reality*, 4.3 (1999), pp. 152–68, doi:10.1007/BF01418152.
[80] 'More than Just a Jacket: Levi's Commuter Trucker Jacket Powered by Jacquard Technology', *Google*, 2017 <https://blog.google/products/atap/more-just-jacket-levis-commuter-trucker-jacket-powered-jacquard-technology/> [accessed 3 November 2024].
[81] Gabriel Loke and others, 'Digital Electronics in Fibres Enable Fabric-Based Machine-Learning Inference', *Nature Communications*, 12.1 (2021), p. 3317, doi:10.1038/s41467-021-23628-5.
[82] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'; Kai Yang and others, 'E-Textiles for Healthy Ageing', *Sensors*, 19.20 (2019), p. 4463, doi:10.3390/s19204463.

smart textiles market is concurrently growing rapidly, in terms of both its size and its commercial significance.[83]

2.1.1.1. Application areas

Despite rapid growth, wearable smart textiles have yet to become mainstream. Efforts are nonetheless underway to increase both their prevalence and their European competitiveness.[84] This highlights the political and economic agendas that are central to the further development of wearable smart textiles – development that is largely driven by well-financed sectors. These include healthcare,[85] military and defence[86] and sectors dealing with exposure to extreme environmental conditions,[87] such as space exploration[88] and certain industrial environments, (e.g. nuclear decommissioning and construction).[89]

These sectors represent key growth areas for wearable smart textiles and include diverse applications. Such applications range from medical monitoring systems to advanced wearable technologies[90] that enhance wearer safety, comfort and communication through temperature regulation via phase change materials and cooling systems.[91] They also manage moisture to prevent heat-related illnesses,[92] monitor vital signs for medical analysis[93] include materials with antimicrobial, chemical or

[83] Shi and others, 'Smart Textile‐Integrated Microelectronic Systems for Wearable Applications'; Koncar, *Smart Textiles and Their Applications*.
[84] 'Accelerating Smart Textile Entrepreneurship by Innovative Cross-Regional, Cross-Disciplinary and Cross-Cultural Value Chains | smartX Project | Fact Sheet | H2020', *CORDIS | European Commission* <https://cordis.europa.eu/project/id/824825> [accessed 12 November 2023].
[85] Yin and others, 'Electronic Fibers/Textiles for Health‐Monitoring'; Alberto Libanori and others, 'Smart Textiles for Personalized Healthcare', *Nature Electronics*, 5.3 (2022), pp. 142–56, doi:10.1038/s41928-022-00723-z; Cedric Cochrane, Carla Hertleer, and Anne Schwarz-Pfeiffer, 'Smart Textiles in Health: An Overview', in *Smart Textiles and Their Applications*, ed. by Vladan Koncar, Woodhead Publishing Series in Textiles (Woodhead Publishing, 2016); Langenhove, *Smart Textiles for Medicine and Healthcare*.
[86] Fernanda Steffens and others, 'Military Textiles - An Overview of New Developments', *Key Engineering Materials*, 812 (2019), pp. 120–26, doi:https://doi.org/10.4028/www.scientific.net/KEM.812.120.
[87] Marco Di Rienzo and others, 'Textile Technology for the Vital Signs Monitoring in Telemedicine and Extreme Environments', *IEEE Transactions on Information Technology in Biomedicine*, 14.3 (2010), pp. 711–17, doi:10.1109/TITB.2010.2048921.
[88] Subrata Mondal, 'Phase Change Materials for Smart Textiles – An Overview', *Applied Thermal Engineering*, 28.11–12 (2008), pp. 1536–50, doi:10.1016/j.applthermaleng.2007.08.009.
[89] *Smart Textiles for Protection*, ed. by Roger A. Chapman, Woodhead Publishing Series in Textiles, 133 (Woodhead Publishing, 2013).
[90] Younes, 'Smart E-Textiles'; Christian Dalsgaard and Rachael Sterrett, *White Paper on Smart Textile Garments and Devices: A Market Overview of Smart Textile Wearable Technologies* (Ohmatex Aps, 2014), pp. 1–11.
[91] Kashif Iqbal and others, 'Phase Change Materials, Their Synthesis and Application in Textiles—a Review', *The Journal of The Textile Institute*, 110.4 (2019), pp. 625–38, doi:10.1080/00405000.2018.1548088; Esfandiar Pakdel and others, 'Advanced Functional Fibrous Materials for Enhanced Thermoregulating Performance', *ACS Applied Materials and Interfaces*, 11.14 (2019), pp. 13039–57, doi:10.1021/acsami.8b19067; Mondal, 'Phase Change Materials for Smart Textiles – An Overview'.
[92] Faheem Ahmad and others, 'Recent Developments in Materials and Manufacturing Techniques Used for Sports Textiles', ed. by Hossein Roghani-Mamaqani, *International Journal of Polymer Science*, 2023 (2023), pp. 1–20, doi:10.1155/2023/2021622; Alireza Saidi and Chantal Gauvin, 'Towards Real-Time Thermal Stress Prediction Systems for Workers', *Journal of Thermal Biology*, 113 (2023), p. 103405, doi:10.1016/j.jtherbio.2022.103405.
[93] Cochrane, Hertleer, and Schwarz-Pfeiffer, 'Smart Textiles in Health: An Overview'; Shirley Coyle and Dermot Diamond, 'Medical Applications of Smart Textiles', in *Advances in Smart Medical Textiles* (Elsevier, 2016), pp. 215–37, doi:10.1016/B978-1-78242-379-9.00010-4.

fire-resistant properties[94] and embed communication devices for team coordination.[95] In these contexts, smart clothing is often worn for extended periods, so comfort and wearability become key, as performance is likely to become negatively impacted if the design results in discomfort, irritation, poor fit, and restricted movement.

2.2. Limitations of the current dominant approaches and the central research gap

Within the diverse realm of smart textiles, which has been described as 'highly interdisciplinary',[96] the majority of efforts bridge 'hard' scientific research disciplines. Here, I discuss the first of the research gaps introduced above.[97]

The current science-driven methods and approaches in these disciplines[98] are crucial for developing the quantifiable components of smart textiles (e.g., flexible sensors, actuators and transistors).[99] However, this dominant approach often relegates textiles to the role of novel vehicles for technology,[100] thereby overlooking the unquantifiable, intangible and nuanced sensory experiences and tactile qualities that a textile can offer.[101] Textiles should not be merely functional but should also be useful, desirable and aesthetically pleasing.[102] This interdisciplinary gap has long been theorised within

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94 Manash Protim Mudoi and others, 'Advanced Fibre Materials in Textile Mudoi, Manash Protim., Singh, Vidushi., Kaur, Harroop., Asmita, Choudhary (2023)', in *Fiber Materials: Design, Fabrication and Applications*, ed. by Jeenat Aslam and Chandrabhan Verma (Walter De Gruyter, 2023), doi:10.1515/9783110992892-202.

95 Ibanez Labiano and others, 'Screen Printing Carbon Nanotubes Textiles Antennas for Smart Wearables'; Isidoro Ibanez-Labiano and others, 'Graphene-Based Soft Wearable Antennas', *Applied Materials Today*, 20 (2020), p. 100727, doi:10.1016/j.apmt.2020.100727; Y. Hao and others, 'Antennas and Propagation for Body Centric Wireless Communications', in *IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics, 2005.* (presented at the IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics, 2005., IEEE, 2005), pp. 586–89, doi:10.1109/WCACEM.2005.1469656; C. Hertleer and others, 'A Textile Antenna Based on High-Performance Fabrics', *IET Seminar Digest*, 2007.11961 (2007), pp. 1–5, doi:10.1049/ic.2007.1085.

96 Ruckdashel, Khadse, and Park, 'Smart E-Textiles'.

97 Acar, Ozturk, and Yapici, 'Wearable Graphene Nanotextile Embedded Smart Armband for Cardiac Monitoring'; Lee and others, 'Conductive Fiber‐Based Ultrasensitive Textile Pressure Sensor for Wearable Electronics'; Lina M. Castano and Alison B. Flatau, 'Smart Fabric Sensors and E-Textile Technologies: A Review', *Smart Materials and Structures*, 23.5 (2014), doi:10.1088/0964-1726/23/5/053001; Loher and others, 'Stretchable Electronic Systems for Wearable and Textile Applications'.

98 Carlos Díaz and others, 'Conceptual Review on Scientific Reasoning and Scientific Thinking', *Current Psychology*, 42.6 (2023), pp. 4313–25, doi:10.1007/s12144-021-01786-5; Berland, 'Explaining Variation in How Classroom Communities Adapt the Practice of Scientific Argumentation'.

99 Chen and others, 'Review of Textile-Based Wearable Electronics'; Ahmed G. Hassabo and others, 'SMART Wearable Fabric Using Electronic Textiles – A Review', *Journal of Textiles, Coloration and Polymer Science*, 20.1 (2023), pp. 29–39, doi:10.21608/jtcps.2022.181611.1148; Maroof Ahmed Choudhury and Aiyer Mahadevan Vaidyanathan, 'E-Textile: Review on Smart Wearable Fabric', 2020 <https://www.semanticscholar.org/paper/E-Textile%3A-Review-on-Smart-Wearable-Fabric-Choudhury-Vaidyanathan/e79719e6dac5d889723a491f09fda3ba2885f12b> [accessed 10 November 2024].

100 Chen and others, 'Review of Textile-Based Wearable Electronics'; Matteo Bianchi and others, 'A Wearable Fabric-Based Display for Haptic Multi-Cue Delivery', in *2016 IEEE Haptics Symposium (HAPTICS)* (presented at the 2016 IEEE Haptics Symposium (HAPTICS), IEEE, 2016), pp. 277–83, doi:10.1109/HAPTICS.2016.7463190.

101 Townsend, Bang, and Mikkonen, 'Textile Designer Perspective on Haptic Interface Design', , p. 2.

102 Jeanne Tan, Anne Toomey, and A. Warburton, 'CraftTech: Hybrid Frameworks for Textile-Based Practice', *Journal of Textile Engineering & Fashion Technology*, 4.2 (2018), pp. 165–69 (p. 165), doi:10.15406/jteft.2018.04.00135.

textile fields,[103] but remains inadequately addressed.[104] This can be seen in (a) the lack of well-designed commercialised smart textiles, which often fall short of expectations from a design perspective (Figure 2.3a) and (b) the absence of a dedicated interdisciplinary journal for smart textiles. Research in this field is predominantly published in discipline-specific journals with a surprising, 88% appearing outside textile-specific publications.[105] The absence of such a platform contributes to the marginalisation of exemplary design practices (Figure 2.3b-2.3d) that successfully integrate both the functional requirements of the textile with the positive attributes of good design.

Figure 2.3. *Examples of wearable smart textiles: a) Axiobionics 'Biosleeve'. Image credit: Axiobionics, LL., https:///www.axiobionics.com/ue-biosleeve/ b)Knitregen prototype wearable therapy garment for stroke rehabilitation. Image credit: Laura Salisbury, www.wtin.com/article/2021/september/130921/wearable-garments-aid-stroke-rehabilitation c) Rheumatoid arthritis smart glove prototype. Image credit: Gozde Goncu-Berk and Nese Topcuoglu. In:* Gozde Goncu-Berk and *Nese Topcuoglu, 'A Healthcare Wearable for Chronic Pain Management. Design of a Smart Glove for Rheumatoid Arthritis',* Design Journal, *20.sup1 (2017)*, pp. S1978–88 (p. 1985), doi:10.1080/14606925.2017.1352717). d) *Robotic, muscle assist concept garment, 'The Power Suit' by Yves Béhar/fuseproject. Image credit: Fuseproject:https://fuseproject.com/work/seismic-poweredsuit*

A recent study centred around the work of textile designer Sandra Wirtanen, working with the engineering sciences in wearable smart textiles, should be highlighted here. Wirtanen's work moves beyond traditional engineering solutions, such as using sticky gel electrodes (commonly used in wearable smart textiles) to explore textile structures that enhance comfort and wearability in a headband design to sense muscle activation in the forehead (Figure 2.4a). However, this work remained exploratory, indicating the need for further development to translate these concepts into practical applications.[106] In the

[103] Marie O'Mahony, *Advanced Textiles for Health and Wellbeing* (Thames & Hudson, 2011); Bradley Quinn, *Textile Futures: Fashion, Design and Technology* (Berg, 2010); Seymour, *Fashionable Technology*; *Techno Textiles: Revolutionary Fabrics for Fashion and Design*, ed. by Sarah Braddock and Marie O'Mahony, Reprinted (Thames and Hudson, 2002).
[104] Pouta, 'Layered Approaches - Woven eTextile Explorations Through Applied Textile Thinking'; Townsend, Bang, and Mikkonen, 'Textile Designer Perspective on Haptic Interface Design', .
[105] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'.
[106] Devendorf and others, 'Craftspeople as Technical Collaborators'.

context of extreme conditions, the designer Crystal Marie Compton's[107] work is also notable. She has hands-on knowledge of materials and garment design developed through prior studies, and she also bridges the interdisciplinary gap to improve the fit and contour of astronaut thermoregulation garments. She does so by developing a smart textile-based-on-body sensor. In order to comfortably and unobtrusively monitor garment contour and its relationship to body contact when the body is in motion (Figure 2.4b), Compton hand-stitches conductive yarns onto a power mesh panel. She then stitches this onto the interior of the astronaut thermoregulation garment. However, Compton's work does not seem to acknowledge the experiential knowledge she brings from design practice, which means that valuable insights about the role and contribution of design expertise in such applications are at risk of being lost.

Figure 2.4. *a) Wearable smart textiles with embedded design expertise: a.) Woven textile electrodes in a stretch headband. In: Devendorf and others, 'Craftspeople as Technical Collaborators', p.8. b) Hand-stitched conductive thread sensor grid. In: Crystal Marie Compton, 'Fit for Space: Leveraging a Novel Skin Contact Measurement Technique toward a More Efficient Liquid Cooled Garment', (unpublished doctoral thesis, University of Minnesota, 2016), p. 60.*

2.2.1. The contemporary landscape of textile design knowledge and its approaches to knowledge construction and cognitive processes

In the light of my aims and objectives (1.2), and the gaps I have highlighted, it is appropriate to outline the contemporary textile design research landscape, specifically its approaches to knowledge construction and the underlying cognitive processes. My goal is to consider what a textile designer can contribute to the interdisciplinary design and development of future wearable smart textiles.

2.2.1.1. Tacit and embodied knowledge

Textile designers have the potential to facilitate new advances. Their unique 'designerly ways'[108]are rooted in both tacit and explicit knowledge:[109]

[107] Crystal Marie Compton, 'Fit for Space: Leveraging a Novel Skin Contact Measurement Technique toward a More Efficient Liquid Cooled Garment', *ProQuest Dissertations and Theses* (University of Minnesota, 2016) <https://search.proquest.com/docview/1853480755?accountid=26642%0Ahttp://link.periodicos.capes.gov.br/sfxlcl41?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&genre=dissertations+%26+theses&sid=ProQ:ProQuest+Dissertations+%26+Theses+Globa>.
[108] Nigel Cross, *Designerly Ways of Knowing* (Birkhäuser, 2007).
[109] Igoe, *Textile Design Theory in the Making*, pp. 122–39.

- Explicitly, textile designers are well versed in textile production and manufacturing technology.
- Tacitly, textile designers possess a deep understanding of materials, their behaviours and the cultural contexts that surround them and their use,[110] all of which designers infuse into their practice and the resulting outcomes.[111] This understanding equips them to meet sophisticated market demands.[112]

These insights encapsulate a 'knowing-by-doing' approach to constructing material knowledge. An approach such as this engages all the senses and focuses on the transformative potential of materials and what they can be made to become rather than their intrinsic properties and composition and how these will inform their behaviour.[113]

Tactile engagement such as this situates textile design within the realm of sensory and aesthetic experience.[114] This embodied knowledge is obtained through hands-on interaction with materials. It involves what Donald Schön has described as 'a reflective conversation with the materials of a situation,'[115] one that facilitates the generation and analysis of knowledge in real time. This exemplifies so-called 'reflection-in-action,'[116] which is fed back into combined manual and cognitive textile design processes.[117] Richard Sennett characterises this as a collaboration between the hand and the mind, whereby the 'intelligent' hand creates a 'repertoire of learned gestures' through repetition.[118] These gestures allow sensory experiences to become embodied and to inform making and thinking. As Michael Polanyi states, 'we know more than we can tell',[119] and this notion is illustrated in textile design. According to Rachel Philpott and Faith Kane, tacit design knowledge is not easily described in words. Rather, it is 'stored' in the practitioner's hands and 'embodied' in the resulting textile artefacts.[120] In a sense, fabric becomes a language, one that can be used to communicate subtle and novel conveyances of sensory awareness and appeal.

This perspective challenges the traditional divide between hands-on and intellectual activities. It aligns with emerging research in embodied cognition,[121] which suggests that 'thinking' emerges from manual practices. Much of what we define as intelligent human behaviour does not take place entirely in

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[110] Kaori O'Connor, 'How Smart Is Smart? T-Shirts, Wellness, and the Way People Feel about "Medical" Textiles', *Textile: The Journal of Cloth and Culture*, 8.1 (2010), pp. 50–67, doi:10.2752/175183510X12580391270029.
[111] Igoe, *Textile Design Theory in the Making*.
[112] Lerpiniere, 'Value Definition in Sustainable (Textiles) Production and Consumption'.
[113] Tonkinwise, 'Knowing by Being-There Making: Explicating the Tacit Post-Subject in Use'.
[114] David Brett, *Rethinking Decoration: Pleasure & Ideology in the Visual Arts* (Cambridge University Press, 2005).
[115] Schön, *The Reflective Practitioner*.
[116] Schön, *The Reflective Practitioner*.
[117] Philpott and Kane, 'Textile Thinking': A Flexible, Connective Strategy for Concept Generation and Problem Solving in Interdisciplinary Contexts'.
[118] Richard Sennett, *The Craftsman* (Yale University Press, 2008), p. 178.
[119] Polanyi, *The Tacit Dimension*, p. 4.
[120] Philpott and Kane, 'Textile Thinking': A Flexible, Connective Strategy for Concept Generation and Problem Solving in Interdisciplinary Contexts', p. 237.
[121] Ihde and Malafouris, 'Homo Faber Revisited'; Lambros Malafouris, *How Things Shape the Mind: A Theory of Material Engagement* (MIT Press, 2013); A. Clark and D. Chalmers, 'The Extended Mind', *Analysis*, 58.1 (1998), pp. 7–19, doi:10.1093/analys/58.1.7; Andy Clark, *Supersizing the Mind: Embodiment, Action, and Cognitive Extension*, Philosophy of Mind (Oxford University Press, 2008).

the individual's mind, but rather is distributed, enacted and mediated through various socio-material forms and material engagement processes.[122] Craft theorist and historian Glenn Adamson's book *Thinking through Craft* reinforces this view. Adamson questions the notion that craft is merely a manual activity, devoid of intellectual engagement, emphasising that craft should be seen not simply as a domain-specific practice but as a methodology: 'Thinking through […] craft? Isn't craft something mastered in the hands, not in the mind? Something consisting of physical actions, rather than abstract ideas?'[123] Adamson thus argues for the importance of recognising craft as a way of doing things that is both intellectual and manual.

Such understanding of craft is integral to the development of wearable smart textiles because, through practice, they offer the potential to facilitate textile designs that are as sensorially pleasing as they are functional. This presents both an opportunity and a challenge for textile design practice and researchers in the field. The opportunity lies in the fact that textile design can potentially offer new ways of doing research and new ways of approaching technological development in this space. Bruna Goveia da Rocha's[124] work represents a good example. Figure 2.5 highlights how she has imparted 'soft' tactile attributes by using machine embroidery to create novel smart textile actuation components through hands-on reflective practices. The challenge lies in communicating such value and contributions in a rapidly changing technological landscape, given the nature of that knowledge.

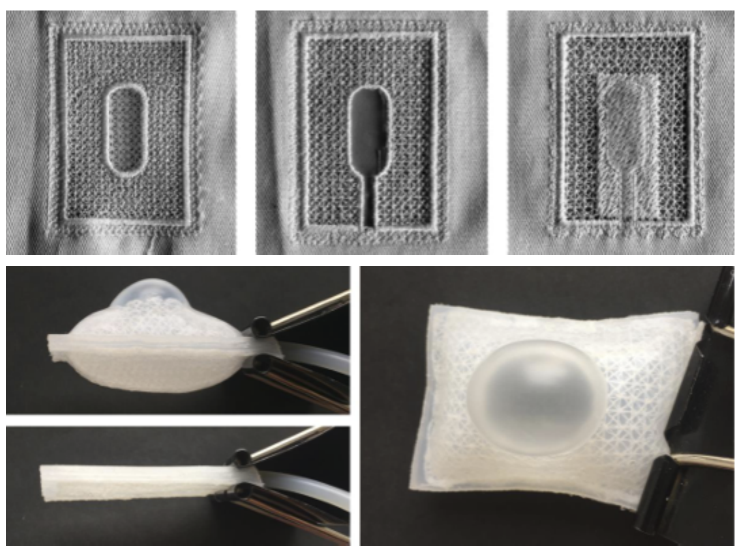

Figure 2.5. *Machine-embroidered inflatable actuator samples. In: Goveia da Rocha, and others, 'Embroidered Inflatables', p.1-4).*

[122] Ihde and Malafouris, 'Homo Faber Revisited', p. 204.
[123] Glenn Adamson, *Thinking through Craft* (Bloomsbury Visual Arts, 2018), p. 1.
[124] Rocha and others, 'Inflatable Actuators Based on Machine Embroidery'.

2.2.1.2. Textile design thinking and cognitive processes

From the contemporary landscape of textile design – where fabric itself becomes a language – we can naturally progress to examine the cognitive processes inherent in this craft. This is the unique 'textile design thinking' that emerges directly from hands-on practice and that is being increasingly theorised[125] and applied to smart textiles research to identify new avenues for innovation.[126]

'Soft', exploratory and experiential approaches to working with textiles influence our cognitive patterns. This has come to be called 'textiles thinking'. Its conceptual origins can be traced back to the writing of textile theorist and curator Pennina Barnett.[127] Expanding on Michel Serres' notion of 'soft logic', Barnett differentiates between 'box-thought', which is rigid and inflexible, and 'sack thought,' which is akin to a fabrics flexible nature.[128] According to Barnett, textiles embody a form of poetic language that epitomises this 'soft logic'. Unlike the exclusionary nature of binary thinking[129] that prevails in smart textiles research,[130] soft logic allows for multiple possibilities. Building on this theory, textile design theorists Pajaczkowska,[131] Igoe[132] and Philpott and Kane[133] have established a connection between the inherent flexibility of textiles and the cognitive processes of textile designers. They advocate for an open, adaptable approach to thought and practice, one that encourages curiosity, experimentation and a willingness to embrace uncertainty. This stands in contrast to a closed mindset, which resists new perspectives and remains static. This dynamic interplay between hard and soft knowledge domains resonates with Donald Schön's juxtaposition of the "hard" knowledge of science and scholarship and the "soft" knowledge of artistry and unvarnished opinion.[134] Philpott's[135] research into adaptable structural textiles embodies this synthesis, showcasing the potential of fusing creative freedom with scientific rigour in textile design, as highlighted by a screen-printed geometry in both its expanded (Figure 2.6a) and contracted (Figure 2.6b) positions.

Those trained in textile design and those in material science have recently and increasingly recognised the potential that exists as these two disciplines come together in new ways. 'The Power of Soft' demonstrates recent research from an interdisciplinary team representing figures from both fields and suggests that if applied materials science and engineering are combined with the tacit knowledge of materials developed through craft processes and hands-on making, 'a new paradigm shift for human-centred, purposeful technologies will be possible' as well as 'new approaches to soft

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[125] Igoe, *Textile Design Theory in the Making*; Pajaczkowska, 'Making Known: Psychoanalysis and the Nine Types of Textile Thinking'.
[126] Pouta, 'Layered Approaches - Woven eTextile Explorations Through Applied Textile Thinking'.
[127] Barnett, *Textures of Memory*.
[128] Barnett, *Textures of Memory*, p. 26.
[129] Barnett, *Textures of Memory*, p. 3.
[130] Winters, 'Why Does Soft Matter? Exploring the Design Space of Soft Robotic Materials and Programmable Machines', p. 127.
[131] Pajaczkowska, 'Making Known: Psychoanalysis and the Nine Types of Textile Thinking'.
[132] Igoe, *Textile Design Theory in the Making*; Igoe, 'In Textasis: Matrixial Narratives of Textile Design'.
[133] Philpott and Kane, 'Textile Thinking': A Flexible, Connective Strategy for Concept Generation and Problem Solving in Interdisciplinary Contexts'.
[134] Schön, *The Reflective Practitioner*, p. viii.
[135] Philpott, 'Entwined Approaches: Integrating Design, Art and Science in Design Research-by-Practice'.

technology'.[136] As such, we are thus presented here with the hypothesis that embracing a 'soft' approach will become increasingly valuable in efforts to 'remain at the cutting edge.'[137]

Figure 2.6. *3D textile folds: Screen-printed foil on Lycra. a) Expanded position; b) Contracted position. In: Rachel Philpott, 'Structural Textiles: Adaptable Form and Surface in Three Dimensions' (unpublished doctoral thesis, Royal College of Art, 2011), p. 110—111*

2.2.1.3. Textile design practices in interdisciplinary smart textile research: 'hard' and 'soft' knowledge domains in practice

Carla Langella outlines the benefits of designers' engagement with the sciences.[138] She emphasises how advancements arising from such engagements echo contemporary values of sustainability, equity and social well-being. For Langella, this transforms technology and societal changes into tangible objects and behaviours.

Interdisciplinary collaborations allow the knowledge embedded within the textile design field to be increasingly applied to other domains through approaches based on hands-on practice.[139] This progression has been described as a 'rupture' and evolution of the 'discrete' discipline of textile design.[140] Traditional boundaries are blurring, giving rise to hybrid designers, who are a mixture of artists, engineers, designers and thinkers.[141]

Anthropologist Lucy Suchman's work[142] challenges traditional design and technical innovation paradigms to include more diverse perspectives and practices. Emmi Pouta has similarly highlighted the

[136] Sarah Morehead and others, 'The Power of "Soft"', *MRS Advances*, 1.1 (2016), pp. 69–80 (p. 79), doi:10.1557/adv.2016.96.
[137] Morehead and others, 'The Power of "Soft"', p. 79.
[138] Carla Langella, 'Design and Science: A Pathway for Material Design', in *Materials Experience 2* (Elsevier, 2021), pp. 259–77, doi:10.1016/B978-0-12-819244-3.00001-6.
[139] 'Interdisciplinary Textiles SIG'.
[140] Craig Bremner and Paul Rodgers, 'Design Without Discipline', *Design Issues*, 29.3 (2013), pp. 4–13 (p. 6), doi:10.1162/DESI_a_00217.
[141] D. West, 'A New Generation', *ICON*, 43 (2007), pp. 57–64.
[142] Lucy Suchman, 'Agencies in Technology Design: Feminist Reconfigurations*', in *Machine Ethics and Robot Ethics*, ed. by Wendell Wallach and Peter Asaro, 1st edn (Routledge, 2020), pp. 361–75, doi:10.4324/9781003074991-32.

need to reframe narratives that are traditionally rooted in a predominantly Western, male-dominated paradigm of design and technical innovation. In emphasising the importance of recognising the varied types of knowledge that underpin cutting-edge technologies she cites Daniela Rosner's book *Critical Fabulations: Reworking the Methods and Margins of Design.*[143] Rosner illustrates this issue by referencing the project 'Making Core Memory', that highlights the crucial roles and contributions of female weavers in assembling memory units (woven planes) for Apollo core rope memory during the 1960s (see Figure 2.7a). This was one of the principal mechanisms by which computers stored and retrieved information during the first two decades of the Cold War. These women's intellectual contributions to innovative computing and technological progress, rooted in craftsmanship and tacit knowledge, went largely unrecognised and unacknowledged.[144] Another example from the Apollo project, is the story of the Apollo spacesuit – an 'unlikely triumph' of the 'soft' over the 'hard'.[145] In 1969, when Neil Armstrong and Buzz Aldrin landed on the moon, they wore soft-shelled suits composed of 21 layers of fabric (Figure 2.7b). Several large-scale military-industrial contractors were well-positioned to win the contract, but Playtex (a manufacturer of bras and girdles) secured the contract by virtue of their intimate experience with the human body. Each suit was custom made for the individual astronaut and assembled by women using Singer sewing machines.[146] More contemporary examples of textile practitioners pioneering advancements in smart textiles can be seen in the DIY crafting smart textile community.[147] These relate to the democratisation of smart textiles and the potential of sensory experiences they offer; however, their contribution to groundbreaking innovations through traditional craft and experimental textiles practices go largely unrecognised.

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[143] Daniela K Rosner, *Critical Fabulations: Reworking the Methods and Margins of Design* (The MIT Press, 2018), doi:10.7551/mitpress/11035.001.0001.
[144] Rosner, *Critical Fabulations*, pp. 2–3.
[145] Nicholas De Monchaux, *Spacesuit: Fashioning Apollo* (MIT Press, 2011), p. 13.
[146] Nicholas De Monchaux, *Spacesuit: Fashioning Apollo* (MIT Press, 2011).
[147] Posch and Fitzpatrick, 'The Matter of Tools'; Buechley and Perner-Wilson, 'Crafting Technology'.

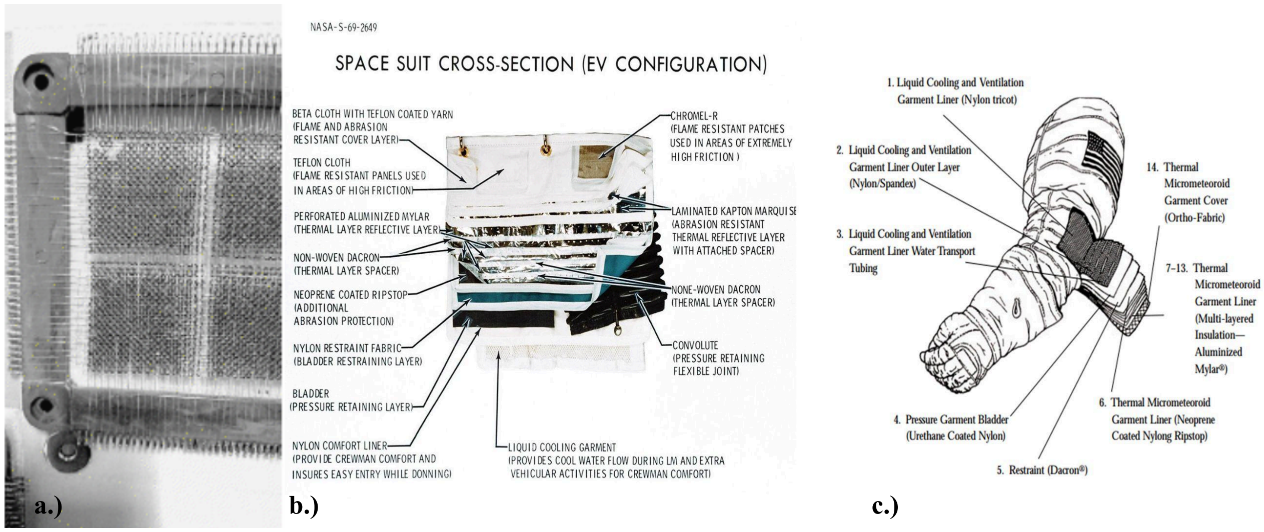

Figure 2.7. *Examples of underappreciated textile expertise in technological innovation a) A 1960s woven core memory plane. In: Daniela Rosner,* Critical Fabulations: Reworking the Methods and Margins of Design *(The MIT Press, 2018),* doi:10.7551/mitpress/11035.001.0001, *p.3. b)Annotated Extravehicular (EV) configuration cross section of the Apollo spacesuit A7L, 1969. NASA. In:Nicholas De Monchaux, Spacesuit: Fashioning Apollo (The MIT Press, 2011)., p.320. c) The 14 layers of the shuttle EMU spacesuit. Image credit NASA,* https://www.nasa.gov/wp-content/uploads/2009/07/188963main_extravehicular_mobility_unit.pdf?emrc=2aa548 *[accessed 26 November 2024]*

Scholars have explored the role of reflective and tacit knowledge and the expressive nature of interactivity in materials. Pouta has investigated weaving as a means to unlock new smart textile concepts and design opportunities.[148] Amy Winters argues that new opportunities within the fields of human–computer interaction (HCI), soft robotics and wearable technology may emerge with the application of methodologies developed within the textile design discipline.[149] These examples reveal how textile designers are evolving to meet the multifaceted challenges and opportunities of their fields. Today, textile designers often work within scientific realms and set benchmarks for effective interdisciplinary engagements. Louise Valentine and others have highlighted such a broader objective by asking, '[H]ow can we build together new models for innovation and wellbeing?'[150] They proposed a shift from considering craft as a mere service to its integration within the knowledge economy to tapping into the value of social capital and innovation in various sectors, from healthcare to education.

This growing awareness nonetheless exposes two related and unexplored research areas:

1. The role of textile design expertise in wearable smart textiles research and development.

[148] Pouta, 'Layered Approaches - Woven eTextile Explorations Through Applied Textile Thinking'.
[149] Winters, 'Why Does Soft Matter? Exploring the Design Space of Soft Robotic Materials and Programmable Machines', p. 405.
[150] Louise Valentine and others, 'Design Thinking for Textiles: Let's Make It Meaningful', *Design Journal*, 20.sup1 (2017), pp. S964–76 (p. 970), doi:10.1080/14606925.2017.1353041.

2. The need to understand how one can effectively navigate different approaches to making and knowing across the sciences and textile design.

Those who are trained in textile design and those in material science are increasingly cognisant of the potential that exists as these two disciplines come together in new ways. There is, however, a lack of literature in (or around) the field of textiles in this regard. Beyond a recognition of the need for unity, there has been little demonstration of how disciplines might actually work together in the development of smart textiles[151] in ways that truly merge the skill sets of those involved.

2.3. The role and contributions of textile design in the smart textile design process

Here I address the second research gap. Despite the invaluable 'soft' knowledge that textile designers possess, their role and contributions remain largely overlooked.[152]Two key factors might account for the undervaluing of textile designers' role in the broader smart textile landscape:

1. The smart textiles field is still in its infancy.
2. Textile design has only relatively recently emerged as a distinct research field.

In scenarios where textile design expertise is considered, tangible textile fabrication skills tend to be valued more highly than 'soft' approaches: this applies to both manufacturing practice and culture. This is not necessarily surprising given the two domains' limited historical engagement. Indeed, spaces for interdisciplinary knowledge-sharing across these domains remain severely limited.[153]

Given these challenges, scholarly attention has only recently shifted toward textile designers' roles and the methodologies they employ. Early researchers such as James Moxey described the role of the textile designer as part artist, part technologist, and part social scientist.[154] This was because of the kinds of activities that textile designers undertook during the design process. Rachel Studd, Colin Gaul and Jasbir Kaur[155] took this further by emphasising specific activities undertaken by textile designers. Gaul and Kaur, for instance, elaborated on the use of technical expertise by textile designers in moving from initial sketches to final production.[156] Igoe, however, critiqued the work of these early scholars for their under-exploration of the unique approaches taken to both making and thinking during the design process.[157] She proposes that textile design has more potential in terms of the emotive experiences textile

[151] Townsend, Bang, and Mikkonen, 'Textile Designer Perspective on Haptic Interface Design', ; Coulter, 'The Designers Leap: Boundary Jumping to Foster Interdisciplinarity between Textile Design and Science'; Walker and others, 'Facilitating Participatory Practice for Smart Textiles'.
[152] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'; Weng and others, 'Smart Electronic Textiles'; Stoppa and Chiolerio, 'Wearable Electronics and Smart Textiles: A Critical Review'; Cherenack and Van Pieterson, 'Smart Textiles'.
[153] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'.
[154] J. Moxey, 'Textile Design: A Holistic Perspective', *Journal of the Textile Institute*, 90.2 (1999), pp. 176–81, doi:10.1080/00405009908690637.
[155] Rachel Studd, 'The Textile Design Process', *The Design Journal*, 5.1 (2002), pp. 35–49, doi:10.2752/146069202790718567; Gale and Kaur, *The Textile Book*.
[156] Gale and Kaur, *The Textile Book*, p. 38.
[157] Igoe, 'In Textasis: Matrixial Narratives of Textile Design'.

design can both elicit and offer. More recent studies by Lean[158] and Winters[159] have begun to address this gap, shedding light on textile designers' roles and contributions to other fields. The overshadowed status of textile designer's potential role and their broader contribution to academic and research domains[160]is further highlighted by the nature of current funding calls. These opportunities are often science-led interdisciplinary projects, rather than those grounded in textile design's own frameworks and intellectual contributions. This highlights how textile design still faces challenges in terms of its recognition as a distinct design discipline with its own methodologies, practices and thought processes.

2.3.1. The impetus of textile design to engage within the field

The fact that smart textiles design often goes unacknowledged provides a unique opportunity for textile designers, not only to showcase their expertise but also to promote and elevate their discipline. Many textiles theorists and practitioners remain committed to advancing their field by increasing the understanding of the potential of textile design approaches (not only as modes of making but also as ways of thinking and doing things). The integration of soft, exploratory textile practices and experiential materials knowledge into the smart textiles field – specifically when it comes to environments characterised by extreme conditions – potentially constitutes a productive and well-funded research avenue. It promises exploration of a myriad of sensory experiences beyond those found in traditional textiles.[161]

This perspective helps to motivate designers to explore and reflect on innovative approaches in previously uncharted research areas. This discourse is imperative in making relevant, but often-tacit, embodied knowledge more transparent. It can also advance methodological research and support the use of such knowledge in new research fields. As Igoe notes, interdisciplinary engagements both reveal individual disciplinary methods and help to identify unique textile design aspects at the edges of the discipline, specifically where it intersects with the sciences.[162]

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[158] Lean, 'Materialising Data Experience Through Textile Thinking'.
[159] Winters, 'Why Does Soft Matter? Exploring the Design Space of Soft Robotic Materials and Programmable Machines'.
[160] 'UKRI Funds Research for a Sustainable Fashion and Textiles Industry', 2023 <https://www.ukri.org/news/ukri-funds-research-for-a-sustainable-fashion-and-textiles-industry/> [accessed 6 July 2024]; 'UKRI Circular Fashion and Textile Programme: NetworkPlus', 2023 <https://www.ukri.org/opportunity/ukri-circular-fashion-and-textile-programme-networkplus/> [accessed 6 July 2024]; 'Innovate UK Textile Fund – Funding Call Now Live – Future Fashion Factory' <https://futurefashionfactory.org/innovate-uk-textile-fund/> [accessed 6 July 2024].
[161] Delia Dumitrescu and others, 'Smart Textiles as Raw Materials for Design Textiles as Design Materials : Inherent and Smart Qualities', in *Shapeshifting Conference: Auckland University of Technology 14-16 April 2014*, 2014, pp. 1–20.
[162] Elaine Igoe, 'The Tacit-Turn: Textile Design in Design Research', *Duck Journal for Research in Textiles and Textile Design*, 1 (2010), pp. 1–11 (p. 8).

2.4. The lack of interdisciplinary guidance to navigate these different approaches to smart textile knowledge creation

The third gap that I have identified in studies to date concerns a lack of guidance for interdisciplinary engagement in the wearable smart textiles field.[163] This research gap is motivated by two key points:

1. It calls for greater understanding of pertinent and contrasting work processes, conceptual frameworks and new design methodologies.[164]
2. It emphasises the need for improved communication channels between disciplines[165] and advocates for the creation of an interdisciplinary journal in smart textiles, which does not yet exist.[166]

The textile design discipline is demonstrating some unique interdisciplinary approaches to production and knowledge. Perhaps we need look no further than this discipline itself in, first, seeking guidance about how different approaches to smart textile knowledge creation might be blended (across both the sciences and textile design) and second, promoting 'softer' approaches to bridging the 'Chapter 3. Methodologies and Methods

[163] Emmi Pouta and others, 'Intertwining Material Science and Textile Thinking: Aspects of Contrast and Collaboration', *DRS Biennial Conference Series*, 2022 <https://dl.designresearchsociety.org/drs-conference-papers/drs2022/researchpapers/168>; Coulter, 'The Designers Leap: Boundary Jumping to Foster Interdisciplinarity between Textile Design and Science'.
[164] Hernandez, 'Introducing a Framework for Crafting E-Textiles', p. 44; Pouta and others, 'Intertwining Material Science and Textile Thinking'; Townsend, Bang, and Mikkonen, 'Textile Designer Perspective on Haptic Interface Design', ; Walker and others, 'Facilitating Participatory Practice for Smart Textiles'.
[165] Kirstein, *Multidisciplinary Know-How for Smart-Textiles Developers*.
[166] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'.

Chapter 3. Methodologies and Methods

3.1. Introduction

My research examines how the textile designer drawing on the 'soft', tacit and embodied knowledge inherent in their discipline can collaborate with the sciences, specifically when it comes to developing smart textiles that are considered from both a functional and sensorial perspective. Addressing this topic requires a combination of qualitative and hands-on methods. In this chapter, I therefore outline the bricolage methodology I have deployed. First, I outline my approach and demonstrate how the methods and methodologies therein are well suited to addressing my aims and objectives; then I illustrate how the combination of these methods have informed my research trajectory and its outcomes. I also discuss how my role as a textile designer evolved during my research. Note that I am going to present what follows sequentially. However, given my study's non-linear course, this sequence does not reflect the chronology of the research methods deployment.

As outlined in Section 1.1.1, this project is situated within a practice-based epistemology. Here I focus on how this positioning shaped my methodological choices. Consistent with my bricolage methodology, methods such as textile sampling, visual thinking and semi-structured interviews were adopted in a non-linear, context-responsive way. Rather than following a fixed plan, they were introduced in response to emerging questions and relationships within the research. This approach supported my understanding of interdisciplinary textile design practices, allowing insights to emerge through making, dialogue and reflection. It also enabled me to remain attentive to the shifting demands of engagement across disciplines while maintaining coherence across a set of practices.

3.2. Bricolage

I selected a 'bricolage' methodology because it allowed me to synthesise elements from fields essential to my research's exploratory and boundary-crossing nature. Within academic research, bricolage is rooted in structural anthropology,[167] and has evolved into a critical, multi-perspectival, multi-theoretical and multi-methodological approach.[168] In the simplest terms, bricolage is undertaken by a bricoleur. The bricoleur actively re-appropriates and combines disparate elements into new and original outcomes, rather than passively accepting pre-existing methodologies. Joyce Yee and Craig Bremner[169] argue that bricolage is, therefore, a useful concept in design research. It allows researchers to deploy available and established

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[167] Claude Lévi-Strauss, *The Savage Mind* (University of Chicago Press, 1966).
[168] Joe Kincheloe L and others, 'Critical Pedagogy and Qualitative Research:Advancing the Bricolage', in *The SAGE Handbook of Qualitative Research*, ed. by Norman K Denzin and Yvonna S Lincoln, 5th edition (SAGE Publications, Inc., 2018); Matt Rogers, 'Contextualizing Theories and Practices of Bricolage Research', *The Qualitative Report*, 17.48 (2012), p. 1, doi:10.46743/2160-3715/2012.1704; Joe L. Kincheloe, 'Describing the Bricolage: Conceptualizing a New Rigor in Qualitative Research', *Qualitative Inquiry*, 7.6 (2001), pp. 679–92, doi:10.1177/107780040100700601; Norman Denzin and Yvonne Lincoln, *Handbook of Qualitative Research.* (SAGE Publications Ltd, 2000).
[169] Joyce Yee and Craig Bremner, 'Methodological Bricolage: What Does It Tell Us about Design?' (presented at the Doctoral Design Education Conference, 2011), p. 3 <https://nrl.northumbria.ac.uk/id/eprint/8822/>.

methods while also creating new tools and techniques to address questions beyond their discipline's established boundaries.

Researchers are increasingly using bricolage methodologies in the textile design field. Such methodologies allow them to explore the potential of hands-on and embodied textile-making processes, specifically those that intersect with different fields of practice.[170] Bricolage is also useful in research into smart textile design, a field that relies on the effective convergence of different perspectives, paradigms and fields of practice. Here, bricolage addresses a methodological gap: It introduces methods from soft, textile-design that consider both functional and sensory design attributes in wearable smart textile development. This in turn, contributes to a field that emerged from the sciences and has traditionally been dominated by quantitative methods.

My research's bricolage methodology has been designed in the context of the value I place on working with things. Indeed, my belief that working with and making objects inspires thought and constructs knowledge is at the heart of my approach. As mentioned in the preface, this philosophical position has emerged from formative creative educational experiences and my beliefs align with discourses and theoretical perspectives found in contemporary textile design research (Section 2.2.1.). This suggests that textile designers develop a distinct approach to both making and thinking. This is referred to as 'textile thinking,'[171] and it comes about through engaging and experiencing textiles' flexible and pliable nature. My beliefs are also consistent with broader practice-based research frameworks, which view creative making as a legitimate mode of inquiry and acknowledge the role of practitioner identity in shaping how knowledge is generated and interpreted[172] (see also Section 1.1.1). Together, these philosophical positions represent my research foundations and have significantly guided my bricolage methodology's development.

My bricolage methodology's scaffold is illustrated in Figure 3.1. It shows where methodologies and methods of data collection, analysis and interpretation intersect. I shall explore individual theoretical and practical components in more depth in proceeding sections. Here, I aim to provide a broad outline of how I combined these forms of enquiry. Two key methodologies have guided my research strategy:

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[170] Cathryn Hall, 'Design for Recycling Knitwear: A Framework for Sorting, Blending and Cascading in the Mechanical Textile Recycling Industry' (unpublished phd, University of the Arts London, 2021) <https://ualresearchonline.arts.ac.uk/id/eprint/17668/> [accessed 4 August 2024]; Laetitia Forst, 'Textile Design for Disassembly: A Creative Textile Design Methodology for Designing Detachable Connections for Material Combinations' (unpublished phd, University of the Arts London, 2020) <https://www.lforst.com/> [accessed 4 August 2024]; Winters, 'Why Does Soft Matter? Exploring the Design Space of Soft Robotic Materials and Programmable Machines'; Clara Vuletich, 'Sustainable Textile Design as Bricolage', *In a Reverse Fashion: A Critical Agenda for Sustainable Fashion*, May, 2014, pp. 1–16; Rachel Philpott, 'Structural Textiles: Adaptable Form and Surface in Three Dimensions' (Royal College of Art, 2011).
[171] Igoe, *Textile Design Theory in the Making*.
[172] Candy and Edmonds, 'Practice-Based Research in the Creative Arts'; Messer, 'Documenting Practice Research'.

1. Research-through-design (RtD[173]), specifically a soft, textile design approach. Here, textile sampling is the core method through which I construct knowledge.
2. Exploratory case studies,[174] suitable for my research in practice.

My RtD is conducted within two projects (labelled CS1 and CS2 in Figure 3.1.), which serve as exploratory case studies. These case studies were set up to act as dynamic, interactive sites for creating smart textile samples, that perform on multiple levels, and for the exploration of the various roles I had to adopt in becoming a smart textiles designer.

[173] Research through design (RtD) was distinguished by Christopher Frayling, who considered the ways in which art and design and research might come together, as one of three possibilities. The term research into art and design refers to historical and theoretical perspectives on art and design, where design practices can be observed by someone not involved in the making process; Research for art and design refers to a focus of study where the end product is an artefact and research through art and design refers to practice and reflection on practice as constituent parts of the research process, alongside an interpretative element: Christopher Frayling, 'Research in Art and Design', *Royal College of Art Research Papers*, 1.1 (1993), pp. 1–5. Research through design, which centralises ongoing reflection throughout the design practice, relies on documentation to ensure that practice serves as a reliable mode of data collection within research: Maarit Mäkelä and Nithikul Nimkulrat, 'Documentation as a Practice-Led Research Tool for Reflection on Experiential Knowledge', *FormAkademisk*, 11.2 (2018), pp. 1–16, doi:10.7577/formakademisk.1818. This approach addresses criticisms related to the relationship between research and practice, particularly concerning the lack of sufficient documentation and reflection on the process.
[174] Sharan. B. Merriam, *Qualitative Research and Case Study Applications in Education: Revised and Expanded from Case Study Research in Education*, Second Edition (Jossey-Bass Publishers, 1998).

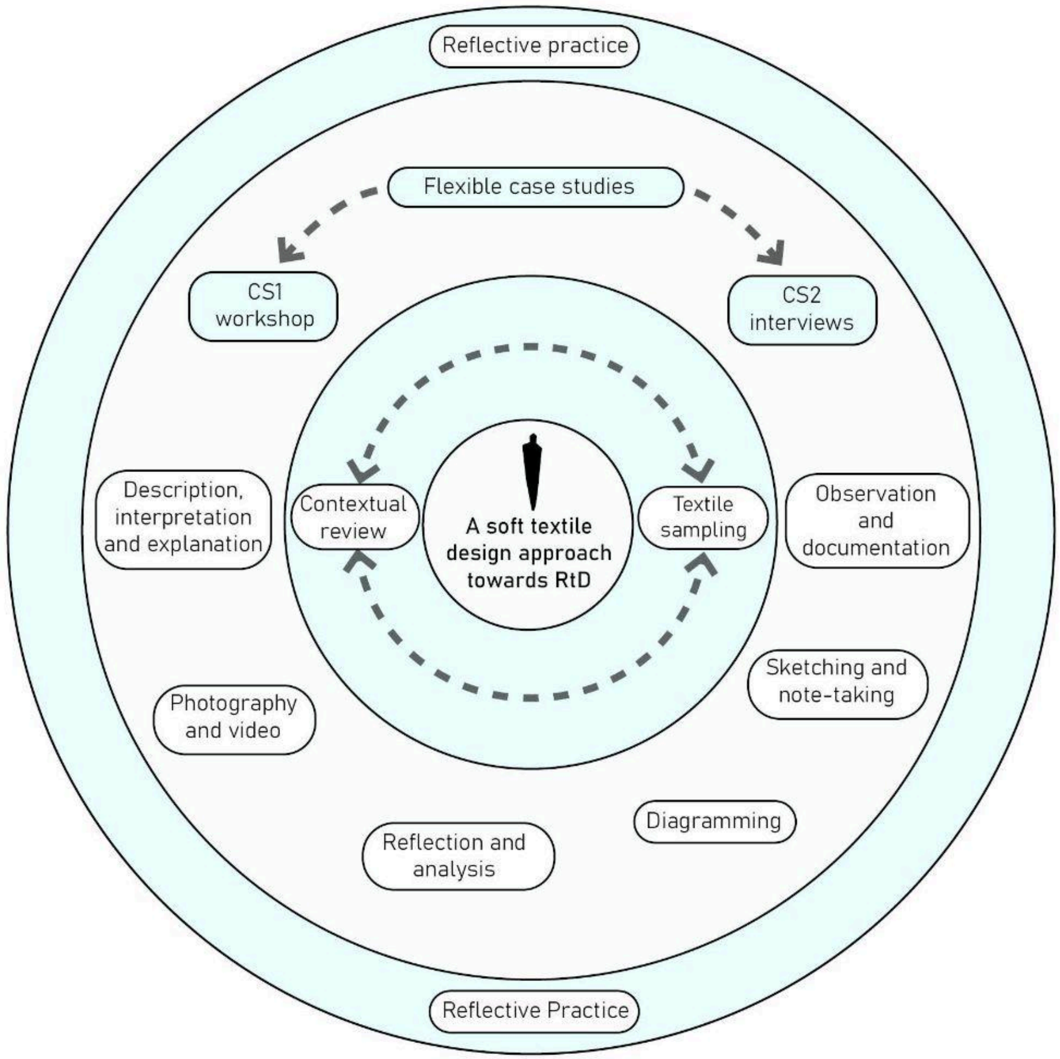

Figure 3.1. *My bricolage methodology's scaffold. The symbol at the centre represents me standing at the centre of the methods I actively pulled together over the non-linear course of my research.*

Reflective practice is central to my bricolage approach, enabling continuous adaptation and learning throughout the research process. Schön's concept of 'reflection *in-action*' and 'reflection *on-action,'*[175] has been employed continuously throughout my research, allowing me to critically engage with the design process, fluidly adapt my methods and develop new insights and understanding. In my RtD, for instance, reflection *in-action* occurs during textile sampling. Responsive adjustments are made based on observations of material behaviour and nuanced interactions between material and technique. Active documentation methods, such as photography, video, sketching and note-taking, also support reflection *on-action.* They do so by providing a rich source of evidence to revisit during analysis. That said, reflective practice is not limited to textile sampling alone, but is central to my research methodology. While introduced here as part of my overarching approach, I discuss more specific examples of how it operates in the individual methods and methodologies employed during my research in the sections that follow. This broader introduction helps to clarify reflective practice's dual role: It is both (1) a reflective tool for critical engagement in the textile design process and (2) a mechanism for developing understanding related to my roles in, and the contributions emerging from, my research.

Diagramming plays a crucial role in this process—both as a reflective tool and analytical visual method:

- As a tool for reflective practice, it helped me to map out the design process and my position as a smart textiles designer. This allowed me to critically analyse my approach and refine my understanding over time.
- As an analytical method, it enabled me to visually synthesise patterns and make complex information more accessible. This offered the insights necessary to address my aims and objectives (1.2).

Contextual review and workshops also play a dual role:

- They enhanced my theoretical and practical understanding of previously unfamiliar materials.
- They help identify knowledge gaps that need to be filled.

Immersion in the case studies and semi-structured interviews further support this reflective process. Notably, it offered additional insights and diverse perspectives beyond my own. Through these activities, I could engage in reflection both *during* and *after* the design process, thereby refining my understanding and approach.

To date, the materials and know-how synthesised and developed within scientific and engineering knowledge frameworks have been necessary when creating smart textiles. My research operates within these traditionally quantitative domains. However, it introduces qualitative approaches to the field through exploratory textile practices. A defining feature of my research is this intersection with the sciences. In this respect, I undertook RtD within two science-led case studies. Both of these focus on textile sampling for the design and development of inner suits with integrated technological components (even if my

[175] Schön, *The Reflective Practitioner*, p. 172.

respective roles and the applications differ). This approach provides a holistic lens. It enables me to consider how soft, exploratory textile practices and experiential knowledge of materials can contribute to wearable smart textile design, specifically when both function and sensory experience are duly considered through engagements between design and science.

3.2.1. Conceptualising 'the material explorer' as the bricoleur

I set out to centralise my role as practitioner-researcher and ground my work in the philosophical positions that engaging with materials can inspire thought and construct knowledge and that creative practice can serve as a valid mode of research. This framing draws on both my prior and ongoing experiences as a textile designer and acknowledges identity as a methodological lens — a position that aligns with Messer's[176] view of identity in practice-based research as dynamic and responsive to interdisciplinary contexts and role negotiation (see also Section 1.1.1). To support this, I established my bricoleur identity as 'the material explorer' during the early stages of my research. As the social scientist Frederick Steier notes, 'we understand and become aware of our research activities as telling ourselves a story about ourselves …'[177] Adopting the 'material explorer' identity could, therefore, help me locate, position, and navigate through the previously unknown territories of smart textile research. This identity was an extension of the 'methodological bricoleur,'[178] one of the multiple perspectives in my bricolage—a perspective that was inspired by soft textile design (as described in Section 3.3) and drew on my own resources (e.g. imaginative and metaphorical thinking).

Given my research's interdisciplinary and exploratory nature, this identity became even more important and supported me in, at least, two ways during the research process:

1. It offered me the creative licence to approach the research with a curious and open outlook.
2. To draw on bricolage's capacity to accommodate 'competing and overlapping perspectives,'[179] I had to be flexible in shifting between the necessarily different roles I adopted in the research. Adopting the identity of the 'material explorer' (as bricoleur) allowed me to do this.

This was necessary for my work with the sciences because it allowed me to create what has been called an 'emergent construction'[180] of my role as smart textiles designer. This refers to the dynamic process involved in developing the skills and understanding needed to embed soft, textile approaches into the wearable smart textiles field. Through this, I could picture, understand, and interpret the object of my research.[181]

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[176] Messer, 'Documenting Practice Research'.
[177] *Research and Reflexivity*, ed. by Frederick Steier, Inquiries in Social Construction (SAGE, 1991), p. 3.
[178] Yee and Bremner, 'Methodological Bricolage: What Does It Tell Us about Design?', p. 3.
[179] Yee and Bremner, 'Methodological Bricolage: What Does It Tell Us about Design?', p. 3.
[180] *The SAGE Handbook of Qualitative Research*, ed. by Norman K. Denzin and Yvonna S. Lincoln, Third Edition (Sage Publications, 2005), p. 4.
[181] *The SAGE Handbook of Qualitative Research*, ed. by Norman K. Denzin and Yvonna S. Lincoln, Third Edition (Sage Publications, 2005), p. 4.

It is worth noting just how important the use of metaphor is in my work. It fits the subjective, embodied, and processual lens through which I conducted my study, and which informed my approach to developing and understanding my research and selecting my methods. In addition, analysing my position within the research also highlighted an aspect of this metaphorical practitioner-researcher identity that I am aware of in hindsight: Having the identity of the 'material explorer' in mind reminded me of the explorative and creative qualities of thought, specifically those that I wanted to keep alive while working in the otherwise technical smart textile research space. It therefore provided a structural mechanism, one that supported me as I shifted into the new domains of understanding I found in the largely 'hard' scientific landscape of current research. Specifically, my metaphorical identity buffered my personal identity from some of the disturbances caused by crossing key thresholds in understanding. In educational theory, these are referred to as 'threshold concepts,'[182] and they notably arose in my research. One such threshold was the realisation that while the consideration of sensory experience occupies an important, often neglected space, functionality imposes an immovable constraint, requiring compromises and flexibility on the part of the textile designer, which, as I found, can be a challenging adjustment.

Figure 3.2, a sketch made at the outset of the study, helps to show the 'material explorer' in action. It depicts my initial position in relation to key aspects of my research. 'Unknown terrain' represents the science-led fields I sought to engage with. 'Unfamiliar materials' refers to novel materials I encountered, which were unfamiliar to me before I embarked on my project (i.e those that had been developed and synthesised within scientific settings). 'Unexplored properties' refers to properties I had not previously encountered (e.g conductivity). As I became more familiar with this research field and others associated with it, however, my position evolved. I now consider these previously unknown domains and material characteristics as integral, and irreversible to my practice and perspective as a smart textiles designer.

[182] Threshold concepts are a framework used in educational theory to describe core ideas within a discipline that are irreversibly transformative to the learner: '[T]hey are akin to a portal, opening up a new and previously inaccessible way of thinking about something' and 'represent a transformed way of understanding, or interpreting, or viewing something, without which the learner cannot progress': J H Meyer and R Land, 'Threshold Concepts and Troublesome Knowledge 1—Linkages to Ways of Thinking and Practising', in *Improving Student Learning—Ten Years On* (OCSLD, 2003).

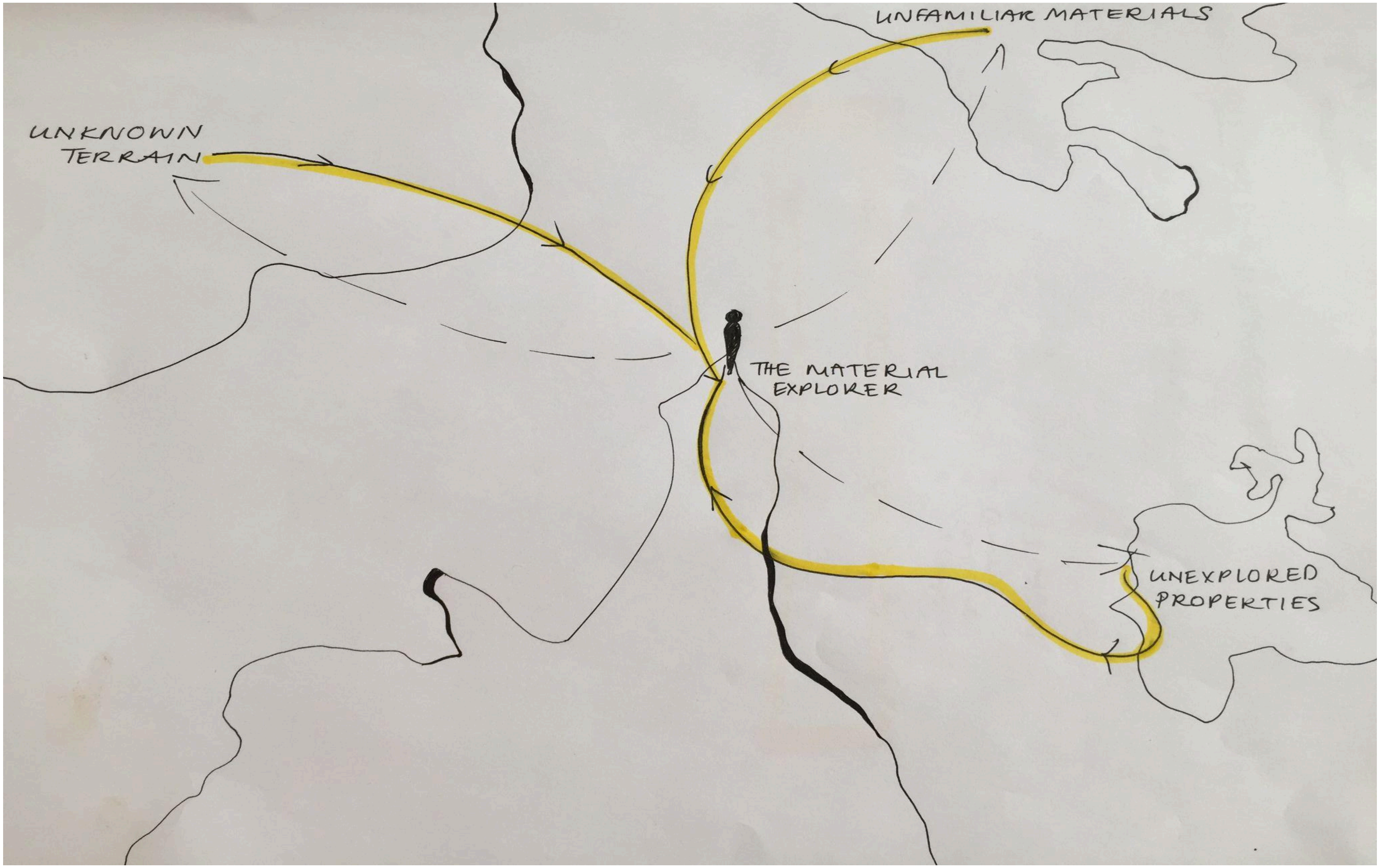

Figure 3.2. *My constructed metaphorical researcher identity: the ‘material explorer’ as practitioner-researcher.*

3.3. A ‘soft’ textile design approach to RtD

The RtD approach was the first of the two methodologies I employed.[183] It notably draws on the work of Christopher Frayling,[184] who considered the act of designing itself as a form of inquiry. In this context, design activities like creating a prototype or model are not just outcomes, they are methods of generating new knowledge.[185]

I chose RtD because I wanted to explore how my skills and expertise as a textile designer could contribute to the design and development of wearable smart textiles. My approach to RtD is, therefore, specifically drawn from soft textile design research. Textile design sampling is, in turn, the core practice through which new knowledge is generated.[186] This approach serves as both a methodology and an approach, combining ‘soft’, hands-on practices with crafts-based applications, thinking, and techniques in the creation of textile samples (Section 3.3.2.). The process of making and refining these samples has generated new insights and ideas related to my research topic. This is consistent with the broader practice-based research context of this research, where the creation of artefacts, material engagement, and reflective insight are understood as valid and interrelated modes of knowledge production.[187] Another rationale for primarily accumulating knowledge through textile sampling was that the outcomes would be useful for textile designers engaging in wearable smart textiles research by offering a textile design perspective emerging from reflecting-*in* and reflecting-*on* actions involved in the design process. At the same time, they also offer insights for scientific researchers, specifically those who engage with textile design and seek to understand textile design approaches. This can, in turn, enhance the potential of engagement between the disciplines.

In line with my overarching bricolage methodology, I adapted the RtD approach’s underlying principles to best suit my research needs. Typically, RtD shares it foundations with action research,[188]

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[183]An additional feature of my use of RtD is that it serves to extend the context of its use beyond its prevalent uses within participatory product and user-centred design and more recently, HCI, in line with Johan Redström’s call to broaden RtD as a form of inquiry: Johan Redström, *Making Design Theory*, Design Thinking, Design Theory (The MIT Press, 2017). This responds to the need for design research to explore new dimensions of practice and knowledge creation, as also discussed by Redström and Heather Wiltse: Johan Redström and Heather Wiltse, *Changing Things: The Future of Objects in a Digital World* (Bloomsbury Visual Arts, 2019).

[184] Frayling, ‘Research in Art and Design’.

[185] Danny Godin and Mithra Zahedi, ‘Aspects of Research through Design: A Literature Review’, *DRS Biennial Conference Series*, 2014 <https://dl.designresearchsociety.org/drs-conference-papers/drs2014/researchpapers/85>; ‘An Analysis and Critique of Research through Design | Proceedings of the 8th ACM Conference on Designing Interactive Systems’ <https://dl.acm.org/doi/abs/10.1145/1858171.1858228> [accessed 16 August 2024].

[186] Typically, RtD encompasses a wide range of design activities, particularly within more established design disciplines like participatory product and user-centred design: ‘What Should We Expect from Research through Design? | Proceedings of the SIGCHI Conference on Human Factors in Computing Systems’ <https://dl.acm.org/doi/10.1145/2207676.2208538> [accessed 22 August 2024].

[187] Linda Candy and Ernest Edmonds, ‘Practice-Based Research in the Creative Arts: Foundations and Futures from the Front Line’, *Leonardo*, 51.1 (2018), pp. 63–69, doi:10.1162/LEON_a_01471.

[188] Frayling described RtD as a ‘form of action research’: Frayling, ‘Research in Art and Design’, p. 5. Similarly, Design Researcher Ilpo Koskinen asserted that design researchers have appropriated this model for RtD: Godin and Zahedi, ‘Aspects of Research through Design’; ‘An Analysis and Critique of Research through Design | Proceedings of the 8th ACM Conference on Designing Interactive Systems’ https://dl.designresearchsociety.org/drs-conference-papers/drs2014/researchpapers/85Godin and Zahedi, ‘Aspects of Research through Design’; ‘An Analysis and Critique of Research through Design | Proceedings of the 8th ACM Conference on Designing Interactive Systems’. Expanding on this connection Maarit Mäkelä and Nithikul Nimkulrat encourage practitioners to engage more fully with the principles of action research, they argue that doing so not only aligns with

which emphasises iterative, problem-solving to instigate change.[189] However, this approach did not fully capture either (a) the nuance of my research study's open-ended and exploratory nature or (b) the focus on my journey as a designer developing an understanding related to what textile design can uniquely offer the wearable smart textile field. I consequently aligned my RtD approach with reflective practice.[190] This reflective approach better represents the way textile design knowledge construction takes place in practice and aligns with its theoretical underpinnings, which emphasise flexibility, responsiveness and open-ended exploration.[191] Thus, my textile-oriented approach to RtD (grounded in reflective practice) is not only a form of research enquiry that is authentic to my approach as a creative practitioner. It is also a valid methodological choice due to its inherent exploratory nature and its flexibility.

This flexibility was crucial when navigating my case studies' unpredictable and high-risk nature. Because of the engagement across disciplines involved, I could not foresee how these projects would progress and whether any of the developed smart textile samples would advance from their initial reflective phases to more strategic stages of testing and refinement (such progression would align with action research principles and project and user-specific requirements). However, the projects did not progress to these stages (for reasons that are detailed in the individual case studies). I nonetheless remained open to the possibility that they might. This approach further validates my choice of RtD as a methodology: It would have allowed me to accommodate advancements had they occurred. RtD's adaptability and its ability to evolve in response to research needs, demonstrates why it was the appropriate choice for navigating the complexities of smart textile design, where project goals can shift and the involvement of multiple stakeholders—each with different priorities and constraints—can make it challenging to predetermine outcomes.

3.3.1. Reflective practice and tacit knowledge

Reflective practice (as described by Donald Schön) and tacit knowledge (as described by Michael Polanyi), are foundational to my 'soft' textile design RtD. These concepts shape how I engage with materials and processes. They also allow for a dynamic and responsive approach to textile sampling.

As outlined in 2.2.1.1., Schön frames reflective practice as an evolving process.[192] This suggests that design is an emergent journey, one that cannot be predetermined but instead unfolds through

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RtD's approaches but also enables practitioners to foster a more critical engagement with their work through a more systematic approach towards reflection: Mäkelä and Nimkulrat, 'Documentation as a Practice-Led Research Tool for Reflection on Experiential Knowledge'.

[189] Action research emphasises continuously reflecting on and reinterpreting issues during the process of creating and evaluating artifacts: John Zimmerman and Jodi Forlizzi, 'Research Through Design in HCI', in *Ways of Knowing in HCI*, ed. by Judith S. Olson and Wendy A. Kellogg (Springer New York, 2014), pp. 167–89 (p. 167), doi:10.1007/978-1-4939-0378-8. It aims to influence or change aspects of the research problem while incorporating insights from other fields to improve it: Colin Robson and Kieran McCartan, *Real World Research: A Resource for Users of Social Research Methods in Applied Settings*, Fourth Edition (Wiley, 2016), p. 199.

[190] While both action research and reflective practice use reflection as a transformative tool, they differ in their intent. The key distinction lies in the notion of strategic action: action research involves 'a deliberate and planned attempt to solve a particular problem or set of problems using a coherent, systematic and rigorous methodology', whereas reflective practice is more fluid and introspective: Tim McMahon, 'Is Reflective Practice Synonymous with Action Research?', *Educational Action Research*, 7.1 (1999), pp. 163–69 (p. 163), doi:10.1080/09650799900200080.

[191] Igoe, 'In Textasis: Matrixial Narratives of Textile Design'.

[192] Schön, *The Reflective Practitioner*, p. 172.

curiosity. Design decisions are made during active engagement in the making process and through subsequent reflection. That said, it is also important to note that, for me, reflecting on the pertinent processes encompassed both (a) analysing the samples, underlying thought processes and hands-on methods involved in their creation and (b) reflecting on the context in which the samples were made. I have, therefore, explored necessary interactions between the various disciplines and sectors required to 'make' the research tangible in the first place. I also selected case studies (see Chapter 4 and Chapter 5) as the context in which my RtD methodology and textile sampling took place.

In textile design, reflective practice can be understood through its roots in craft practices, where the sensory, experiential and hands-on aspects are key.[193] According to textile theorists Gaul and Kaur, craftspersons prioritise the act of making-by-hand above all else.[194] The craft literature further emphasises that making-by-hand is not just a technical activity. It is a form of 'thinking through making,' where knowledge is generated from the interaction between maker and materials.[195] This kind of hands-on making is crucial for understanding materials, refining techniques and generating insights that are embedded in the making process.

This aligns with Polyani's notion of 'tacit knowledge' (see Section 2.2.1.1.).[196] Along with reflective practice, this notion has been central to my work because I carry it as a creative practitioner and it crucially informs my thinking and decision making.[197] Over the years, I have gained a good understanding of how one can combine and manipulate materials and techniques to meet textiles' sensory/aesthetic and functional requirements (as tailored to their intended applications). Building on this foundation, my extensive, hands-on experience therefore embodies what Cameron Tonkinwise refers to as 'material knowing'[198]—a type of knowledge obtained through making materials and working directly with materials. This 'material knowing' constitutes a nuanced understanding gained through direct engagement. And it differs from the systematic material knowledge typically found in materials science, which is prevalent in the smart textiles field.

In this research, I have drawn on both tacit knowledge from hands-on experience and explicit knowledge, including practical aspects such as sourcing yarn or booking equipment. I have also drawn on

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193 In increasingly theorised textile design methodologies, the act of making holds central importance, with researchers framing their work as 'reflective-craft-practices' or 'crafts-design approaches. See for instance: Hall, 'Design for Recycling Knitwear'; Forst, 'Textile Design for Disassembly'; Helen Paine, 'Laser Shaping : A Method for Controlling the Elastic Behaviour of Stretch Fabrics for a Targeted and Graduated Compressive Effect on the Body' (Royal College of Art and Design, 2015); Kate Goldsworthy, 'Laser-Finishing: A New Process for Designing Recyclability in Synthetic Textiles', *PQDT - UK & Ireland*, June, 2012 <https://www.proquest.com/dissertations-theses/laser-finishing-new-process-designing/docview/1779551712/se-2?accountid=14597%0Ahttp://sfx.hbz-nrw.de/sfx_ulbms?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&genre=dissertations&sid=ProQ:Pr>; Philpott, 'Structural Textiles: Adaptable Form and Surface in Three Dimensions'.

194 Colin Gale and Jasbin Kaur, *The Textile Book*, p. 63.

195 Adamson, *Thinking through Craft*; T'ai Smith, *Bauhaus Weaving Theory* (University of Minnesota Press, 2014); Peter Dormer, *The Art of the Maker* (Thames and Hudson, 1994).

196 Michael Polanyi, *The Study of Man (Routledge Revivals) The Lindsay Memorial Lectures 1958*, 1st edn (Routledge, 2013), pp. 12–13, doi:10.4324/9781315889740.

197 Tacit knowledge is still a relatively new field of research. Some key references as they relate to creative practice are as follows: Ingold, *Making*; Schön, *The Reflective Practitioner*; Polanyi, *The Tacit Dimension*; Polanyi, *Personal Knowledge*.

198 Tonkinwise, 'Knowing by Being-There Making: Explicating the Tacit Post-Subject in Use', p. 5.

a workshop focused on bilateral knowledge exchange with a scientific research team along with technical insights from literature reviews and both industry and academic events. This blend of insights has been crucial in guiding the integration and securing of polymer optical fibres and fluidic systems in wearable smart textiles.

While my RtD approach is grounded in reflective practice, I have also selectively drawn from other research traditions to better suit my work's specific needs. This aligns with my overarching bricolage methodology. I have, for instance, chosen the spiralling model from action research[199]rather than adhering to the traditionally circular models often found in reflective practice.[200] The spiralling model better reflects the ongoing exploration, growth and deepening understanding central to my work. In my selection I nonetheless set aside its associated, underlying notions of strategic problem-solving and planned interventions, adapting it instead to align with exploratory and open-ended nature of textile design.

At this point, it is worth returning to my metaphorical research identity as 'material explorer,' which is central to visualising this adaptation to the model of reflective practice within my RtD approach. Figure 3.3 depicts 'the material explorer's' journey as the research passes through two case study projects situated in 'hard', challenge-led research domains. Here, Schön's concepts of reflection-*in*-action and reflection-*on*-action underpin both (a) the act of making and refining textile properties in line with both their technical properties and design qualities, (i.e soft texture and flexible drape) (depicted by spiral at the centre) and (b) the case study projects themselves (depicted by the second and third loops). In the latter, I have reflected on how the research addressed the challenge of creating softer versions of traditionally rigid devices and components to enhance wearability of wearable smart textiles. This in turn, contributed to my broader goal of developing the notion of making and embedding textile design thinking into efforts in the field. This occurs at the end of each case study, with insights from the first informing the second. I have also incorporated what Stephen Scrivener has called the 'final' reflection,[201] (depicted by the final loop). This is contained in the concluding chapters of my thesis, where I reflect on my 'soft' approach. Indeed, the thesis itself becomes a comprehensive reflection of my journey as a textile designer within the research.

In Figure 3.3, the processual path through my case study projects is traced with a needle and a thread. This signifies both the idea that bricolage sews diverse aspects of the research together and that the bricoleur's identity is valuable to the research process outcomes. 'The material explorer' approaches the first case study from a grounding in curiosity and craft-based textile design practices, interwoven with knowledge and materials developed within the sphere of science and engineering. The second case study

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199 Stephen Kemmis and Mervyn Wilkinson, 'Participatory Action Research and the Study of Practice', in *Action Research in Practice: Partnership for Social Justice in Education*, ed. by Bill Atweh, Stephen Kemmis, and Patricia Weeks (Routledge, 1998), pp. 21–22.
200 Kolb's Experiential Learning Cycle and Gibbs' Reflective Cycle are two widely used circular reflective practice models: Kolb, *Experimental Learning*; Graham Gibbs, *Learning by Doing: A Guide to Teaching and Learning Methods* (FEU, 1988).
201 Stephen AR Scrivener, 'Towards the Operationalisation of Design Research as Reflection in and on Action and Practice', in *2nd Conference of Doctoral Education in Design: Foundations for the Future*, ed. by David Durling and Ken Friedman (presented at the Doctoral Education in Design: Foundations for the Future, Staffordshire University Press, 2000), pp. 387–94 (p. 392) <https://dl.designresearchsociety.org/conference-volumes/29>.

has more in common with the science and engineering sphere. This is as a result of its longer duration, more applied nature and the fact that I was embedded within a science-led research team; this is illustrated by its placement further to the right of the diagram.

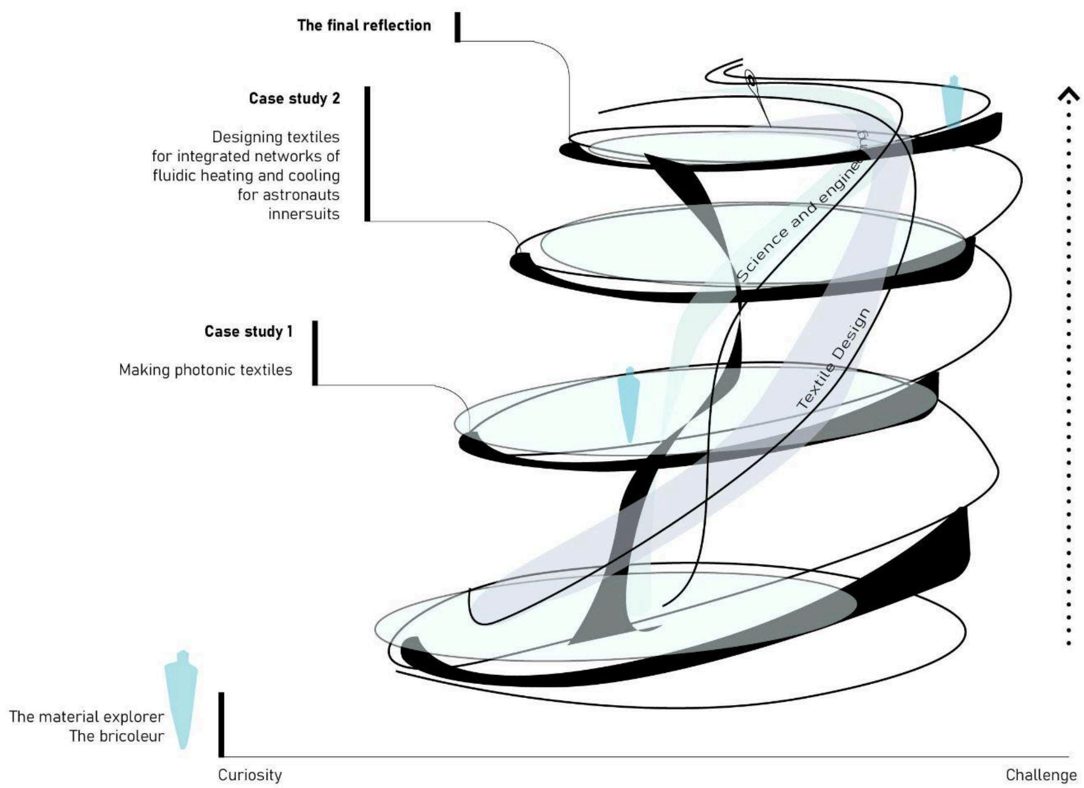

Figure 3.3. *The practitioner-researcher's journey through the reflective research cycles, divided according to the case studies.*

3.3.2. Textile sampling

In the textile design context, making is often presented in the form of the sample. 'The sample'[202] can in turn be considered a 'signature pedagogy.'[203] It is a fundamental element of the discipline, one that supports the progression and presentation of ideas, thought, and aesthetic, sensory and functional attributes. Typically, samples 'pledge back' to a 'rich, multi-modal language', a variety of textual, auditory, visual, and tactile materials,[204] that have been selected and curated by the designer to inform and inspire the design process.

Sampling was an appropriate method for my research because it is one of textile design's signature pedagogies. It embodies both the sensory, experiential aspects of making that are fundamental to the discipline and the craft traditions that textile design processes and practices emerge from. I employed this pedagogy because it offered me a familiar route into the smart textile design field (which I had no prior knowledge of). It also helped me explore how textile or 'soft' methods, practices and values can be integrated into the smart textile design landscape. At the beginning of my research, I engaged in a hands-on study (Appendix A), which supported the development of my research aims and objectives. Sampling allowed me to transition from purely theoretical exploration to a more tangible, practical engagement with previously unfamiliar, but important properties (e.g. conductivity).

The open-ended and suggestive nature of samples[205] aligns with a central RtD component: it is always about research *on the future.*[206] This characteristic reflects the field of smart textile design in, at least, three respects:

1. It is still in the process of being defined and therefore has no established methods for successfully thinking and making across disciplines.
2. It is positioned as a field of exploration, with emphasis on possibility.
3. The 'indeterminate nature' of textiles creates a 'network of strands that link different disciplines.'[207] This makes textile sampling particularly suited to interdisciplinary contexts.

[202] Typically a square snippet of fabric and used in both academic and industry settings, they are considered proposals for future design processes which host information about their maker, making and intended application through carefully considered interactions of colour, pattern, texture, structure and drape.
[203] Ellen Sims and Alison Shreeve, 'Signature Pedagogies in Art and Design', in *Exploring More Signature Pedagogies: Approaches to Teaching Disciplinary Habits of Mind*, ed. by Nancy L. Chick, Aeron Haynie, and Regan A. R. Gurung (Routledge, 2023).
[204] Igoe, 'In Textasis: Matrixial Narratives of Textile Design', p. 61.
[205] In the smart textile domain Delia Dumritescu and others proposed that smart textiles samples might be considered as unfinished 'raw materials for design' which hold the potential to enrich future design processes which they were not designed for. Delia Dumritescu et al. 'Smart Textiles as Raw Materials for Design' in Proceedings of Shapeshifting Conference: Auckland University of Technology. 14-16 April 2014, p.6
[206] 'An Analysis and Critique of Research through Design | Proceedings of the 8th ACM Conference on Designing Interactive Systems'.
[207] Pennina Barnett, *Textures of Memory: The Poetics of Cloth*, ed. by Polly Binns and others (Angel Row Gallery, 1999).

In keeping with my metaphoric conception of myself as 'the material explorer', as *bricoleur,* navigating different disciplines and working with unfamiliar materials, these samples act as souvenirs of my journey through the expanding smart textiles field. They represent discoveries articulated in a form that 'speaks' to the discipline of textile design, encapsulating the hands-on knowledge and insights I have gained and brought back to enrich the field.

While the characteristics noted above made sampling an appropriate method for use within this study, it was both inevitable and expected that my work would involve samples. Textile design and the sciences share their method of deriving ideas and concepts using hands-on approaches and procedures. And, just as prototyping is a key method employed within the physical sciences and engineering, samples are textile design's signature pedagogy.

In each of the case studies, I saw my role as a 'maker' or *practitioner-researcher* engaging with scientific teams in the smart textile field as central to my approach. It is important to note that relationships between makers, materials, and various experts (e.g. textile technicians, suppliers, and scientists) were fundamental to the development of the samples. Feedback was typically provided verbally during these sessions, focusing on what was working, what adjustments were needed and how the samples aligned with project requirements. This effort emphasises the importance of multiple parties working together. It goes against the image of a solitary designer working with material—an image that typically comes to mind when people consider crafts-based practice.[208]

Combining 'know-how' and 'know-what' learning modes, I sought to address each case study's specific goals. Various textile techniques were employed in the case studies to combine my existing knowledge of materials and techniques with the exploration of new, unfamiliar materials and the specific applicative challenges they present. My goal was to understand how combining and manipulating these elements might alter the textiles' sensory and tactile attributes. Techniques like embroidery, mixed media, and knitted textiles combined with reflections on these practices in my research's multidisciplinary projects, allowed me to explore how a textile designer's skills and innovative thinking can contribute to future practices in smart textile design, specifically when it comes to enhancing relevant sensory and functional qualities.

3.3.3. Active documentation

To support my reflection both *in* and *on* the sample-creating process, I used photography and video as forms of 'active documentation'.[209]There was, however, a risk of forgetting some technical information related to the samples—information that was necessary for their analysis. Hirohito Shibata and Kengo Omura[210] have noted that handwriting has a low cognitive load. This allows individuals to think, listen,

[208] Sennett, *The Craftsman*.
[209] Nancy de Freitas, 'Towards a Definition of Studio Documentation: Working Tool and Transparent Record', *Working Papers in Art and Design*, 2 (2002), pp. 1–10.
[210] Hirohito Shibata and Kengo Omura, 'Effects of Writing and Drawing by Hand', in *Why Digital Displays Cannot Replace Paper*, by Hirohito Shibata and Kengo Omura (Springer Singapore, 2020), pp. 125–53, doi:10.1007/978-981-15-9476-2_7.

and talk while simultaneously taking notes. This motivated me to take handwritten notes about the samples.

3.3.4. Visual thinking

Alongside photographic and video documentation, my research made liberal use of sketches and diagrams. As Gray and Malins describe in *Visualizing Research*[211] techniques like sketching, diagramming, and mapping are useful for supporting research progressions, interpretations and analyses. Indeed, sketching has been a valuable technique throughout my research. It allows me to represent abstract thoughts in their initial and developing stages before they are clear enough to draw in diagrams. This aligns with conclusions Vinod Goel, Gabriela Goldschmidt and Schön[212] have reached. They explain how sketching can help researchers in both (a) exploring and materialising ideas and (b) externalising thoughts and gaining feedback during the thinking process. As psychologist Barbara Tversky writes, 'when thought overwhelms the mind, the mind puts it into the world, notably in diagrams and gestures;' these 'external gestures of the mind'[213] organise space, convey thinking and abstractions, and support future thought, which can then be 'reinspected, rearranged and revised.'[214] These findings were borne out in my research process, in which sketching enabled me to further develop my ideas.

Sketches also facilitated communication during meetings with scientific project contributors and technical experts from the textiles field. Such sketches notably conveyed my methodological thinking and understanding of where my research was positioned (Figure 3.4 and 3.5). Annotations, in turn, played a critical role in improving the sketches' clarity and comprehensibility. Adding technical information and metaphorical thinking that was related to my understanding of the research's positionality and the smart textiles field's spatial relations allowed my sketches to illustrate how the respective knowledge domains intersect.

When sketching, I preferred to use pen and paper (loose sheets or notebooks) rather than digital tools. As Shibata and Omura[215] note, sketching by hand is central to spontaneous creativity: Designers tend to rely on physical methods for sketching while 'drawing tools on computers require users to know what they want to draw beforehand, making it difficult to think while drawing.' Manual and embodied sketching also allows me to reflect-*in*-action,[216] which engages my tacit knowledge and demonstrates important links between the thinking mind and the feeling body.

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[211] Carole Gray and Julian Malins, *Visualizing Research: A Guide to the Research Process in Art and Design* (Taylor & Francis Group, 2016) <http://ebookcentral.proquest.com/lib/rcauk/detail.action?docID=4406199> [accessed 2 October 2024].
[212] Vinod Goel, *Sketches of Thought* (MIT Press, 1995); Gabriela Goldschmidt, 'The Dialectics of Sketching', *Creativity Research Journal*, 4.2 (1991), pp. 123–43, doi:10.1080/10400419109534381; Schön, *The Reflective Practitioner*.
[213] Barbara Tversky, 'The Cognitive Design of Tools of Thought', *Review of Philosophy and Psychology*, 6.1 (2015), pp. 99–116 (p. 99), doi:10.1007/s13164-014-0214-3.
[214] Tversky, 'The Cognitive Design of Tools of Thought', p. 112.
[215] Shibata and Omura, 'Effects of Writing and Drawing by Hand', p. 125.
[216] Schön, *The Reflective Practitioner*.

As my thinking advanced, I turned to diagrams in order to interpret, analyse, and communicate the research. Sketches had helped me to 'free' thought, but diagrams offered me a way to 'freeze' it.[217] Gray and Malins have observed that artists and designers tend towards more visual/experiential learning styles.[218] They also found that visual structures (including diagrams and matrices) offer powerful tools for creatively analysing and making sense of data.[219] This is because these structures force researchers 'to extract and select from a large amount of data' and to 'present [their] understanding in a single visual.'[220] Diagrams thus align with Schön's notion of reflection-*on*-action,[221] and they serve as my key analysis method during the research. I made liberal use of diagrams, specifically to highlight both the role of textile design and my evolving position within the case studies (Chapter 4 and Chapter 5). (I initially produced the diagrams by hand and later digitised them using Adobe tools to enhance their clarity).

[217] Steven M. Smith, 'Getting Into and Out of Mental Ruts: A Theory of Fixation, Incubation, and Insight', in *The Nature of Insight*, ed. by Janet E. Davidson and Robert J. Sternberg (The MIT Press, 1994), pp. 229–52, doi:10.7551/mitpress/4879.003.0011.
[218] Gray and Malins, *Visualizing Research*, p. 2.
[219] Gray and Malins, *Visualizing Research*, p. 143.
[220] Gray and Malins, *Visualizing Research*, p. 146.
[221] Schön, *The Reflective Practitioner*.

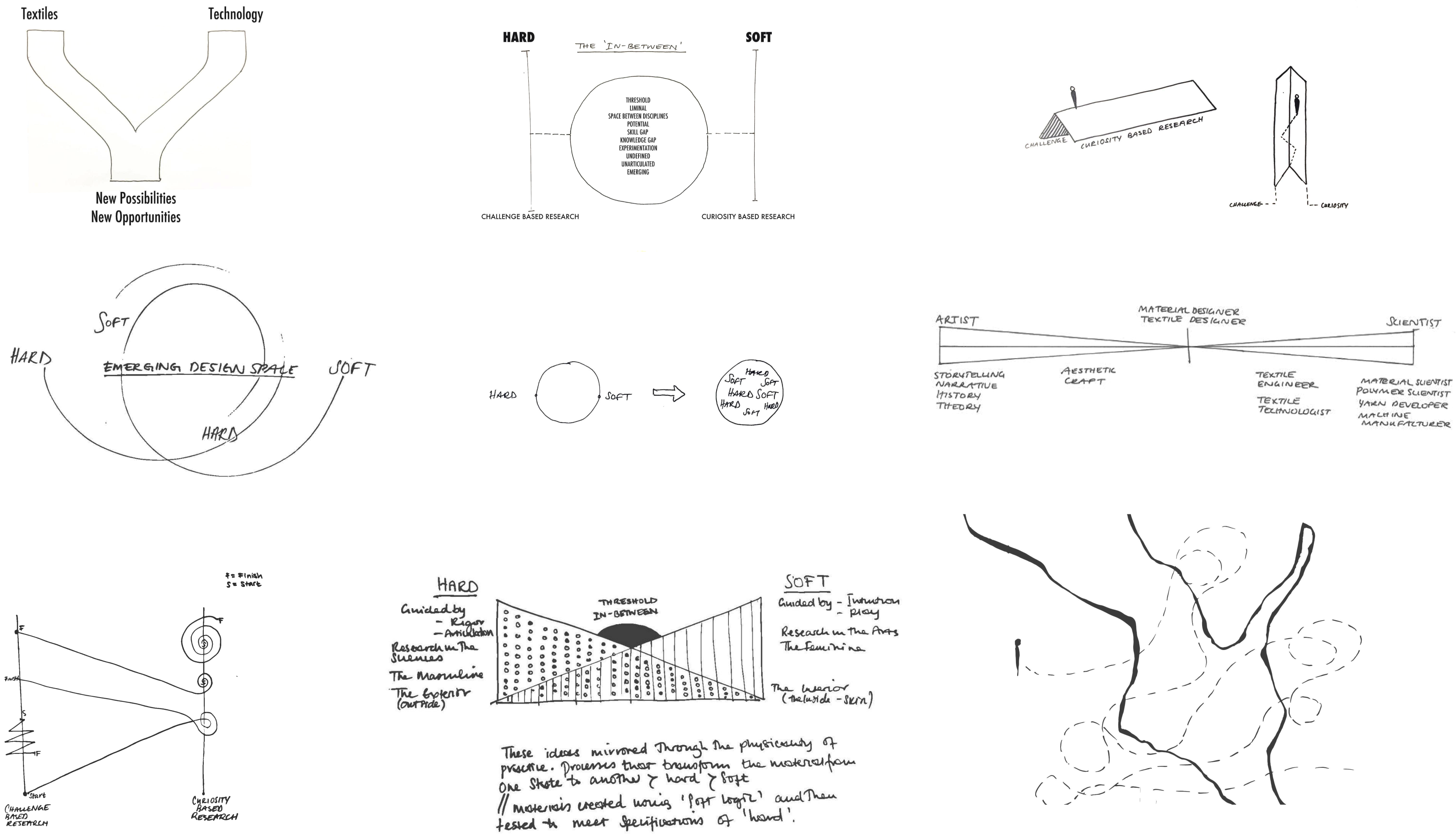

Figure 3.4. *Hand-drawn, annotated sketches—a visual thinking technique for focusing on the research landscape and my position therein. Copyright: Claire Felicity Miller.*

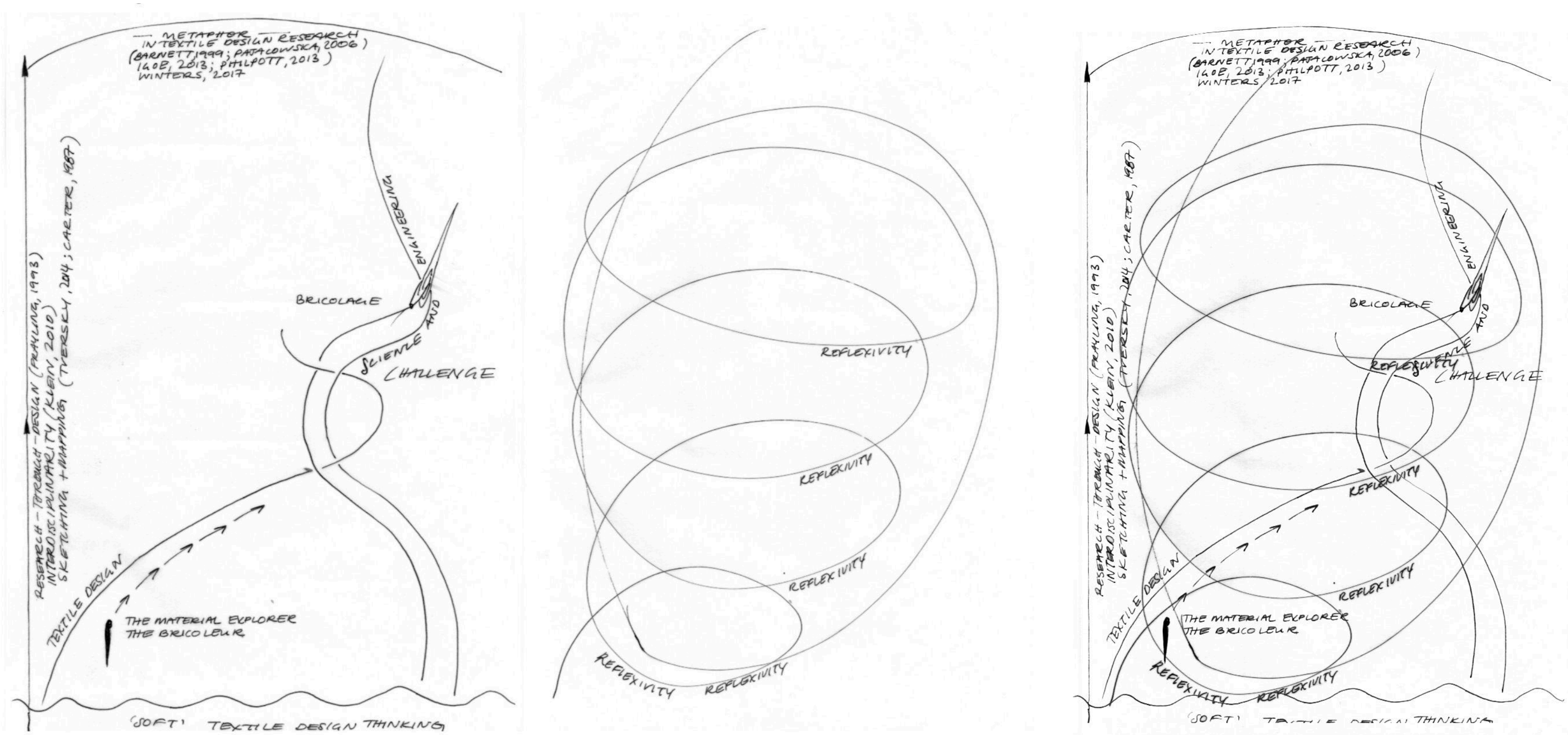

Figure 3.5. *Hand-drawn, annotated sketches—a visual thinking technique for focusing on my research methodology. Copyright: Claire Felicity Miller.*

3.4. The case study

I have described the role of RTD and 'soft', textile approaches in my methodology. This has included discussion of (a) the interplay between reflective practice and tacit knowledge and (b) how these two elements have informed both my choice of design activity (textile sampling) and my methods for recording and exploring my findings. In the following, I shall focus on the second methodology that goes into my bricolage approach: the case study.

Originating in the social sciences, case studies are a well-established research strategy.[222] They have been used to study contemporary phenomena in real-life contexts using multiple sources of evidence.[223] Their flexible design[224] and methods also make them suitable for the reflective practice embodied in this thesis and discussed above (Section 3.4.2). The case study was also apt for my research because of its focus on context. Indeed, creativity is context-dependent in that it is a situated practice influenced by both embodied experiences and the surrounding environment.[225] As a creative practitioner, I was also actively involved in science-led research environments. These contexts, the relationships between them, and what was learned from them were central to my research aims. Case studies therefore seemed to present rich means of understanding them.

For my research purposes, I conducted two exploratory case studies using a practice-based approach. Early-stage exploratory sampling (Appendix A) had already highlighted the value of hands-on material handling and engagement across disciplines. Thus, in each case study, I sought to (a) embed myself within an interdisciplinary environment between science and textile design and (b) undertake hands-on textile sampling within it. Each case study is therefore, 'bounded' by the scope of the project and its context, timeframes, location and duration. Within the project boundaries, I have been able to examine both my 'soft', textile design approach in context and my position as a textile designer within them.

Both exploratory case studies resemble my approach to making because their primary textile sampling technique is knitted textiles and they focus on innersuit sample creations. The first case study consisted of making photonic textiles as samples for 'smart basics'. The second case study aimed to design textiles for integrated networks of fluidic heating and cooling for astronaut inner suits. Although the first case study had been set up to enable interdisciplinary and hands-on engagement, I faced challenges when trying to maintain interdisciplinarity in the process. The second case study was, therefore, designed to make working across disciplinary boundaries easier. These two exploratory case studies form a rich body of data for this thesis. I describe them in some detail in Chapters 4 and 5.

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[222] Thomas A. Schwandt and Emily F. Gates, 'Case Study Methodology', in *The SAGE Handbook of Qualitative Research*, ed. by Yvonna S Lincoln and Norman Denzin, 5th edition (SAGE Publications, Inc., 2018), pp. 600–630.
[223] Colin Robson, *Real World Research: A Resource For Users of Social Research Methods in Applied Settings*, Third edition (Wiley, 2011), p. 136., citing Robert K.Yin (2009) *Case Study Research: Design and Methods,* 4th edn (London, Sage, 2009).
[224] Robson, *Real World Research: A Resource For Users of Social Research Methods in Applied Settings*, p. 135.
[225] Malinin, 'How Radical Is Embodied Creativity?', p. 9.

My goal was to embed myself (as a practitioner-researcher) in active, science-led research settings focused on smart textiles. Scientific labs are at the cutting edge of current knowledge and offer fertile ground for design innovation.[226] I therefore chose academic research labs as my research environment. Yet, the relevant teams lacked prior knowledge of design. I was, therefore, optimistic that my design input would contribute towards advancing the wearability and comfort of innovative smart materials beyond the research stage. When selecting research teams to engage with on my exploratory case studies, I was guided by the degree to which my textile design expertise might support technological advancement. The location of each lab was also a factor.[227]

In both cases, I initiated and developed the opportunities through my professional and academic networks, actively shaping the projects to bring textile design expertise into science-led contexts. Each case study was designed and set up to ensure its relevance to creating textiles that balance functional and sensory attributes for use in extreme conditions and the corresponding need for comfort and safety improvements. My exploratory case studies therefore took place in the contexts of nuclear decommissioning (Chapter 4) and space exploration (Chapter 5).

3.5. The contextual review

Before examining my exploratory case studies, I shall discuss the final element of my methodology: the contextual review. Such a review comprises two key strands: (1) a literature review followed by (2) a review of practice. A combination of these has allowed me to deepen my understanding of the smart textile field. To gain insights through active participation in smart textile design, I engaged in various professional and academic events, such as conferences, trade shows, workshops and interviews with specialists. As the following examples show, the insights gained from these experiences have complemented what I learned through my literature review, which, in turn, informed my approach to making.

Although my contextual review and textile sampling (the key method in my RtD) are presented separately, they are intrinsically linked. My hands-on sampling was informed by literature reviews, and my hands-on sampling drove my thinking and understanding of the field. When combined and used alongside the hands-on methods of knowledge production gained through the textile design sampling process, my contextual review's two strands enable an implementation of the case studies. This serves as an essential part of my RtD process. Together, they allowed me to review the field of wearable smart textile design and to position me as a material explorer.

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[226] Tobie Kerridge, 'Designing Debate: The Entanglement of Speculative Design and Upstream Engagement' (unpublished doctoral, Goldsmiths, University of London, 2015), p. 93 <https://research.gold.ac.uk/id/eprint/12694/> [accessed 4 January 2025].

[227] While I had successfully worked across continents within the preliminary study, in order to maximise the potential that strong relationships could have on the project outcomes, I chose projects that were easily accessible and based exclusively in the UK.

3.5.1. Literature review

The literature review in Chapter 2 serves multiple purposes. It establishes the existing smart textile research landscape. It also identifies an interdisciplinary gap in the research, one that is evidenced by the lack of (a) a journal specialising in the interdisciplinary smart textile field[228] and (b) textile design expertise in the broader field. Parts of that literature review (e.g. Section 2.2.1.1.) shaped the development of my preliminary investigative studies. These, in turn, influenced the development of my research research focus and aims and objectives (Appendix A). My reading specifically focused on works that would inform how I could engage with the smart textiles field. I paid special attention to works by textile design researchers discussing the influence that hands-on approaches to materials and processes exert on thinking and developing ideas.[229] In this, I was guided by my philosophical outlook and my initially intuitive understanding that cognitive processes often emerge from manual practices (3.3.).[230]

The literature review was also conducted with the aim of furthering my research's interdisciplinary objectives. Through it, I acquainted myself with domain-specific terminology and the technical elements and constraints of unfamiliar materials. This approach helped (a) bridge knowledge gaps between myself and scientific project contributors (which rendered our engagement more effective), (b) frame existing research in a format that scientific project partners and funders would accept and (c) contribute to establishing a 'common language'[231] between researchers and practitioners crossing artistic and scientific boundaries. Textile designers do not traditionally undertake literature reviews, but they are becoming part of an increasingly established practice. Now, practitioners spend more time in the concept development phase of projects that combine art, design, and science.[232]

3.5.2. Professional and academic events

The following professional and academic events highlight my research's nature and allowed me to foster professional relationships that could support its ongoing development:

- In 2018, I exhibited my work at the 'Materials Research Exchange' (MRE). There, I came into contact with UK-based university labs actively developing smart textiles.[233] CS1 was developed through engagement with contacts I established at the MRE;
- In 2019, I presented findings from my early research stages at the RCA's 'Work-in-Progress' show. Here, I met the director of the HCRS, ICL. This meeting set me up to become an embedded textile design researcher on the FAIR-SPACE project.

[228] Ruckdashel, Khadse, and Park, 'Smart E-Textiles'.
[229] Philpott, 'Entwined Approaches: Integrating Design, Art and Science in Design Research-by-Practice'.
[230] Ihde and Malafouris, 'Homo Faber Revisited'; Malafouris, *How Things Shape the Mind*.
[231] Camilla Groth and others, 'When Art Meets Science : Conditions for Experiential Knowledge Exchange in Interdisciplinary Research on New Materials', *International Conference of the Design Research Society Special Interest Group on Experiential Knowledge (EKSIG), 2019*, 2019, pp. 1–14 (p. 7).
[232] Valentine and others, 'Design Thinking for Textiles: Let's Make It Meaningful', p. 966.
[233] 'Materials Research Exchange 2018, Ai a Resounding Success - Innovate UK Business Connect', 2018 <https://iuk-business-connect.org.uk/news/materials-research-exchange-2018-ai-a-resounding-success/> [accessed 2 December 2024].

- In 2018, I was a panellist at the 'Wearable Technology Show'. There, I explored challenges around balancing design and technology in smart garments. I also took questions from industry professionals who emphasised how the field needs textile designers' expertise.

While viewing the 'Moving to Mars' exhibition at the Design Museum in 2019, I viewed space suits and cooling garments on display. This experience offered a direct encounter with historical and contemporary advancements in my area of study, which further inspired my exploration of the intersection between textile design and wearable technology. I also presented my work at the Research-through-Design conference at Delft University of Technology (TU Delft) in 2019. There, I discussed my approach to smart materials with an audience specialising in design research. This allowed me to position myself as a textile design researcher engaging exploratively with science-led smart textiles within the event's broader theme of 'frictions and shifts.[234]'

3.5.3. Immersion and workshop

Alongside academic events, conferences and exhibitions, I decided to immerse myself in the field of smart textile design. Immersion draws on field research principles, which emphasise the importance of developing familiarity with one's object of study.[235]This includes becoming familiar with the research group's specialised language. All of these are key to understanding a group and the social rules it follows. Such knowledge can also enhance the quality of data collected by other means.[236]

My goal in turning to immersion was to familiarise myself with the field of smart textile design and to develop an associated 'know-how' relevant to it. The workshop (detailed in Appendix C) is an example of immersion. It was designed to promote interdisciplinarity and to blend experiential 'know-how' with theoretical 'know-what.' This was, in turn, intended to leverage insights from the literature with expertise in materials. The workshop also sought to help textile designers gain the technical and practical skills they need to handle and work with unfamiliar materials. There was also a focus on working with POFs (discussed in Chapter 4) and showcasing Schön's idea that design is a 'conversation between the materials of a situation.'[237] Designers often build expertise through repeated experiences with familiar materials. This means that the effective handling of new and unfamiliar materials (like POFs) requires direct, hands-on engagement.

Regarding my own learning, the workshop extended both the theoretical insights from my literature review and the hands-on expertise gained by engaging with subject matter experts. It also informed my thinking about how the materials could be effectively used and handled during textile design processes. This complements broader immersion strategies. These included field trips to research facilities, show-and-tell meetings with specialists, embedding myself as a textile design researcher within a project team, interviewing project contributors and engaging with scientific researchers.

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[234] Claire Felicity Miller, 'Crafting Material Innovation and Knowledge through Interdisciplinary Approaches', *Proceedings of the 4th Biennial Research Through Design Conference*, 2019, pp. 1–16, doi:10.6084/M9.FIGSHARE.7855916.V2.
[235] Ruth Barley, 'Why Familiarise?', *Social Research Update*, 62, 2011, pp. 1–4.
[236] Barley, 'Why Familiarise?'
[237] Schön, *The Reflective Practitioner*, p. 172.

Smart textiles designers Sarah Walker and Anna Piper[238] argue that the workshop format is an excellent means to stimulate interdisciplinary thinking through making. Educational researchers Rikke Ørngreen and Karin Tweddell Levinsen write that workshops are ideally suited to present new competencies, practices, knowledge, and ideas.[239] To foster interdisciplinary exchange and enhance interdisciplinary understanding, I therefore led a hands-on workshop (detailed in Appendix C). Through immersion and the workshop, I was able to identify potential areas where textile design could intervene in science-led smart textile research. I also gained a more nuanced understanding of (a) the challenges and opportunities my project presented and (b) each of the team members' perspectives and values.

3.6. Semi-structured interviews and reflexive thematic analysis

Before examining my exploratory case studies, I shall discuss the final element of my methodology, a series of semi-structured interviews, analysed using reflexive thematic analysis.[240] This method was selected to extend findings from my embedded practice and hands-on making in the technically demanding, science-led domain of CS2. Guided by Flick's *knowing-with* interview format,[241] this approach enabled me to foreground participants' subjective viewpoints beyond my own, and through reflective co-construction, to assemble a fuller picture of the research environment I was embedded within.

Nine members of the FAIR-SPACE project participated (see Table 3.1): four textile-design practitioners and researchers and five scientists or engineers (including contributors from robotics, materials science and medical engineering), two of whom occupied hybrid roles spanning technical design and academic management responsibilities. I selected participants based on their active involvement in the RCA-HCRS, ICL partnership, either as members of the FAIR-SPACE, ICL team I engaged with during textile sampling, or through one of the three strands of the broader RCA-HCRL, ICL partnership (Appendix V). Recruitment followed approved ethical protocols, with informed consent obtained (Appendix W) and transcripts anonymised during analysis. Interviews lasted between 40 and 60 minutes and are held on the RCA research repository as an external dataset.[242] I oriented my questions around three core areas:

1. Participants' experiences of engagement during the project.
2. Their constructions of success and value within it.

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[238] Sarah Walker and Anna Piper, 'The Textile Designer 2.0: A Workshop Guide for Future Workshop Facilitators in Smart Textiles', in *Intersections; a Conference Exploration Collaboration in Textile Design Research* (Loughborough University, 2017), pp. 1–16 <www.lboro.ac.uk/textile-research/intersections.>.
[239] Rikke Ørngreen and Karin Tweddell Levinsen, 'Workshops as a Research Methodology', *Electronic Journal of E-Learning*, 15.1 (2017), pp. 70–81.
[240] Virginia Braun and Victoria Clarke, 'Reflecting on Reflexive Thematic Analysis', *Qualitative Research in Sport, Exercise and Health*, 11.4 (2019), pp. 589–97, doi:10.1080/2159676X.2019.1628806; Virginia Braun and Victoria Clarke, 'Using Thematic Analysis in Psychology', *Qualitative Research in Psychology*, 3.2 (2006), pp. 77–101, doi:10.1191/1478088706qp063oa.
[241] Uwe Flick, *An Introduction to Qualitative Research*, 4th edn (London: Sage Publications Ltd, 2009).
[242] Claire Miller, 'Dataset Accompanying Thesis "An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines"', RCA research repository, 2024, doi:https://doi.org/10.60624/M8P1-YA33.

3. The tensions, frictions and moments of productive negotiation they encountered.

Open-ended prompts allowed conversations to follow participants' own emphases and disciplinary language, supporting the emergence of unanticipated insights.

To support reflection on disciplinary boundaries and to help participants situate their practice within a broader disciplinary spectrum, I introduced Jensenius's[243] diagram of intra-, multi-, cross-, inter- and transdisciplinarity as a visual prompt (Appendix Y). Some interviews also included mapping and sketching exercises to chart participant's project journeys. These activities helped elicit tacit and affective dimensions of experience, which supported the development of my thinking.[244]

The interview transcripts were analysed using Braun and Clarke's reflexive thematic analysis,[245] an approach which is consistent with my practice-based, bricolage methodology through its flexibility and reflexivity. I transcribed each interview in full, listening back multiple times to develop familiarity before moving into coding. Using Quirkos software,[246] I worked inductively, allowing patterns to surface from the data while remaining attentive to my position in the research. No formal feedback of findings was provided to participants due to time constraints. The preliminary thematic strands included:

- Negotiating disciplinary authority — how different forms of expertise were valued, recognised, or marginalised;
- Invisible labour and emotional work — the unacknowledged coordination, care and relational effort required to sustain engagement;
- Conflicting measures of success — contrasting expectations and evaluative criteria across scientific and design domains;
- Structural misalignments — tensions between institutional timelines, funding structures and the rhythms of creative practice.

I understood these not as fixed conclusions, but as early, interpretive signposts that supported my thinking and making in CS2 and suggested directions for deeper analysis, particularly in relation to the evolving identity of the smart textile designer and the affective dimensions of engagement across disciplines.

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[243] Alexander Refsum Jensenius, 'Disciplinarities: Intra, Cross, Multi, Inter, Trans', Post, *ARJ*, 12 March 2012 <https://www.arj.no/2012/03/12/disciplinarities-2/> [accessed 8 August 2025].
[244] Anna Bagnoli, 'Beyond the Standard Interview: The Use of Graphic Elicitation and Arts-Based Methods', *Qualitative Research*, 9.5 (2009), 547–70 (p. 548) https://doi.org/10.1177/1468794109343625.
[245] Braun and Clarke, 'Reflecting on Reflexive Thematic Analysis'.
[246] Graham R. Gibbs, 'Using Software in Qualitative Analysis', in *The SAGE Handbook of Qualitative Data Analysis*, ed. by Uwe Flick (London: SAGE Publications, 2013), p. 277

Table 3.1. CS2 Interview participants

Participant code	Primary Role/ Discipline	Institution/ Affiliation (at the time of interview)
01	Engineer (Robotics)	HCRS, ICL
02	Engineer (Electronics)/ Designer and Project Coordinator	HCRS, ICL
03	Engineer (Robotics)	HCRS, ICL
04	Textile Designer / Researcher	HCRS, ICL/RCA
05	Textile Designer / Researcher	HCRS, ICL/RCA
06	Senior Tutor Textile & Material Science / Project Facilitation	RCA
07	Programme Head (Textiles)	RCA
08	Textile Design Research	RCA
09	Engineer (Medical Robotics)	HCRS, ICL

3.7. Chapter synthesis: organisational structures and hierarchies

Across this chapter, I have outlined the methodological framework underpinning my research, including the practice-based and reflective approaches used within both case studies, the immersive and contextual activities that informed them and, in the case of CS2, the perspectives gathered through semi-structured interviews. While I describe these methods in detail within their respective sections, they were embedded within distinct project environments, each with its own hierarchies, formal reporting lines and points of intersection between disciplines.

Figures 3.6 and 3.7 synthesise this information in a visual overview of the organisational structures for CS1 and CS2 respectively, showing formal project roles, reporting relationships and my practitioner–researcher position within each structure. In Figure 3.7, the roles of interview participants are also identified, linking the perspectives analysed in Section 3.6 to their positions within the wider project hierarchy. Together, the diagrams provide a clear reference for understanding the organisational context in which each case study was situated.

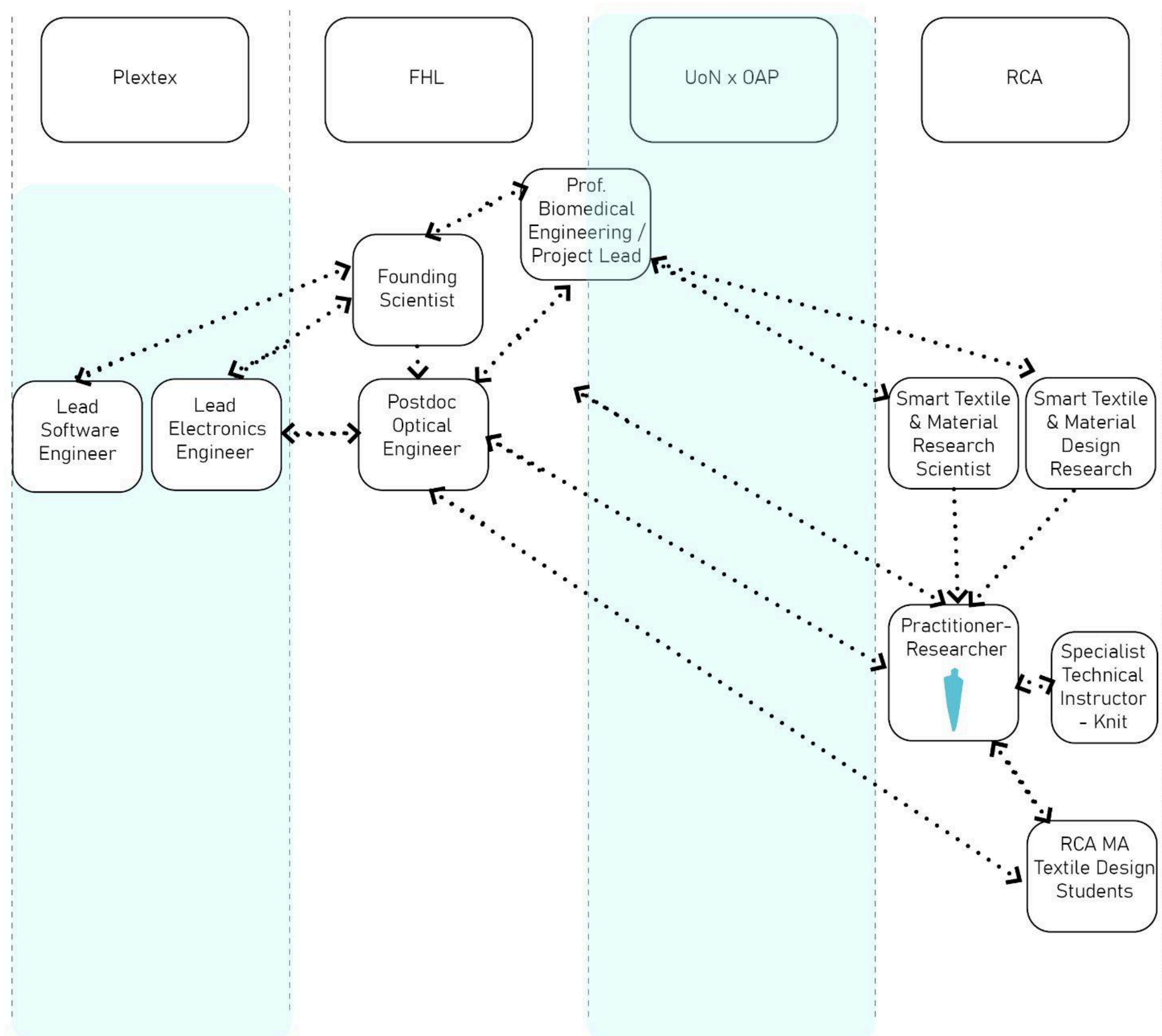

Figure 3.6. *My position as practitioner-researcher within the organisational structure and reporting lines of CS1.*

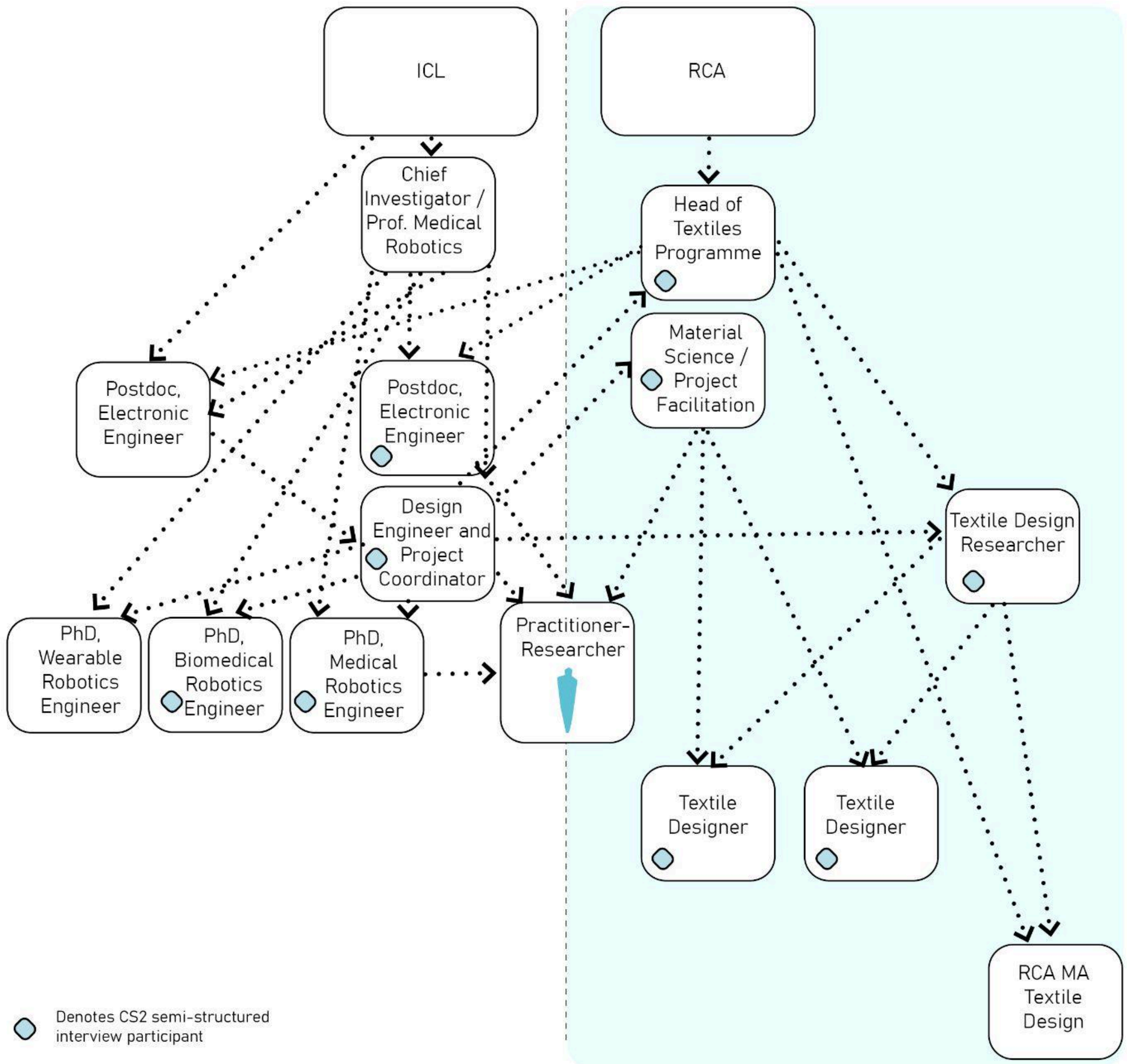

Figure 3.7. *My position as practitioner-researcher within the organisational structure and reporting lines of CS2, also indicating the participants who were interviewed for this study.*

Chapter 4. Case study 1—Making photonic textiles

4.1. Project background and objectives

In this chapter, I explore the technical and creative processes underpinning the development of photonic textile samples through the case study ‘Making Photonic Textiles’. This case study frames my role and contribution within a multidisciplinary project and examines how the textile designer can bridge the technical and sensory dimensions of wearable smart textiles. The project, which took place over three months,[247] was led by Footfalls and Heartbeats Ltd. (FHL),[248] a smart textiles technology company, whose focus is on the development of knitted-textile-based sensors alongside the University of Nottingham’s (UoN) Optics and Photonics Research Group (OAP).[249] The primary objective of the project was to test the feasibility of a wearable photonic textile integrated system as a valid option for enhancing operator productivity and comfort during nuclear decommissioning operations.[250] Within this context, my research explored how textile design expertise can contribute to creating textiles which balance technical performance and the experiential dimensions of wearability.

As the key research associate from a textile design perspective, in this project I produced a series of knitted samples (Appendix G) that incorporated POFs as OFSs. This involved integrating and securing the ‘flexible’ OFS materials, which are representative of the scientific and engineering territories explored in my research, in a way that ensured their functionality (see Appendix B). Simultaneously, I focused on embedding the critical design properties necessary for their intended final application as a base layer inner-suit garment. These included fabric handle, drape, and texture, which are key to comfort and wearability and appearance. The intention was to identify successful techniques and yarn combinations that could, at a later stage, be embedded into the garments, which aimed to monitor vital biometric signals, such as heart rate variability (Appendix B), to alert safety personnel to bring in operators from a decommissioning environment in response to signs of early-onset heat stress. To accomplish this, I engaged with the ‘hard,’ previously unfamiliar technical considerations specifically related to the functional requirements of the OFS. An analysis of the approach adopted towards the development of sensorially pleasing, comfortable and functional textiles demonstrates how textile design expertise can enhance interdisciplinary research projects in smart textiles.

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[247] This work was part of a funded project under the Small Business Research Initiative (SBRI), Innovate UK (IUK), and Sellafield Ltd., which oversees the safe operation and cleanup of the Sellafield Nuclear site in Cumbria, UK: While the project successfully demonstrated technical feasibility during Phase One, it did not receive further funding to progress to the Phase Two (see Appendix J).

[248] ‘Footfalls & Heartbeats’, *Footfalls & Heartbeats* <https://www.footfallsandheartbeats.com> [accessed 24 November 2024].

[249] ‘Optics and Photonics Research Group - The University of Nottingham’ <https://www.nottingham.ac.uk/research/groups/optics-and-photonics-research-group/index.aspx> [accessed 24 November 2024].

[250] The proposed ‘smart basics’ integrated system was envisioned as a wearable smart textiles garment capable of monitoring both the operator and the suit environment, via an upgraded communication system for real-time monitoring of temperature, humidity, and airflow. The gathered data would form a feedback loop, providing crucial information for adjusting environmental conditions and determining when to remove an operator from a hazardous environment owing to early signs of heat stress (see Appendix J).

4.2. Design approach and sampling

An important research aim was to infuse 'softness' into the context of nuclear decommissioning to support a more interdisciplinary process in wearable smart textile design and development. However, it was clear that I would first need to engage with complex technical considerations and establish a solid knowledge base. I therefore adopted a multifaceted approach that included a comprehensive review of the technical literature ('know-what'; see Appendix B); discussions with scientific project contributors and experts in technical knitting, and design, facilitation and co-participation in a hands-on workshop ('know-with' and 'know-how'; see Appendix C).

The literature review (Appendix B) was conducted in alignment with the commercial focus of FHL by focusing on the use of OFSs in knitted textiles, and served two critical purposes. First, it was a required project deliverable to evaluate whether the project's initial scoping phase met the criteria for securing additional funding in the second phase. Second, it served as the foundation for the project's subsequent practical stages within this case study. By providing a comprehensive understanding of current advancements and challenges in photonic knitted textiles research, it offered valuable insights into how POFs might be integrated into textiles with the aim of optimising their functionality as wearable sensors. This knowledge facilitated a more precise appraisal of the project's potential, streamlined the sampling process and provided a base from which I could tentatively approach aesthetic exploration (see Figure 4.1).

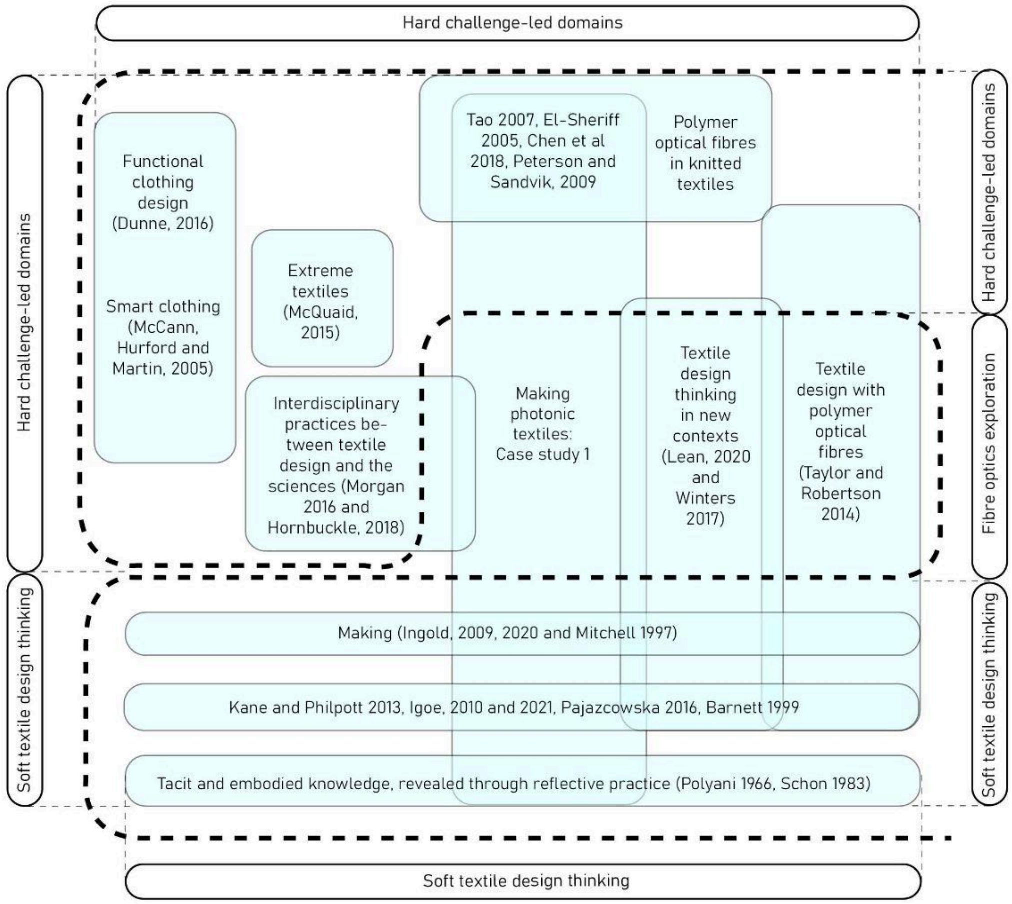

Figure 4.1. *Overview of the literature review relevant to Case Study 1.*

The workshop was instrumental in enhancing my understanding of the properties of POFs, providing me with both practical and technical insights into the use of POFs as sensors in wearable healthcare monitoring. Figure 4.2a. illustrates a key moment in the workshop, where one of my scientific partners demonstrated the practical use of OFS, supporting my understanding of their optimal use to monitor heart rate (Appendix C). Using software and equipment developed by FHL, I learned about the importance of correct on-body OFS placement, at the temple (Figure 4.2b), abdomen (Figure 4.2c) and chest (Figure 4.2.d), as well as how to stabilise the fibre to ensure precise and reliable readings which were then visualised using FHL proprietary software (Figure 4.2e).

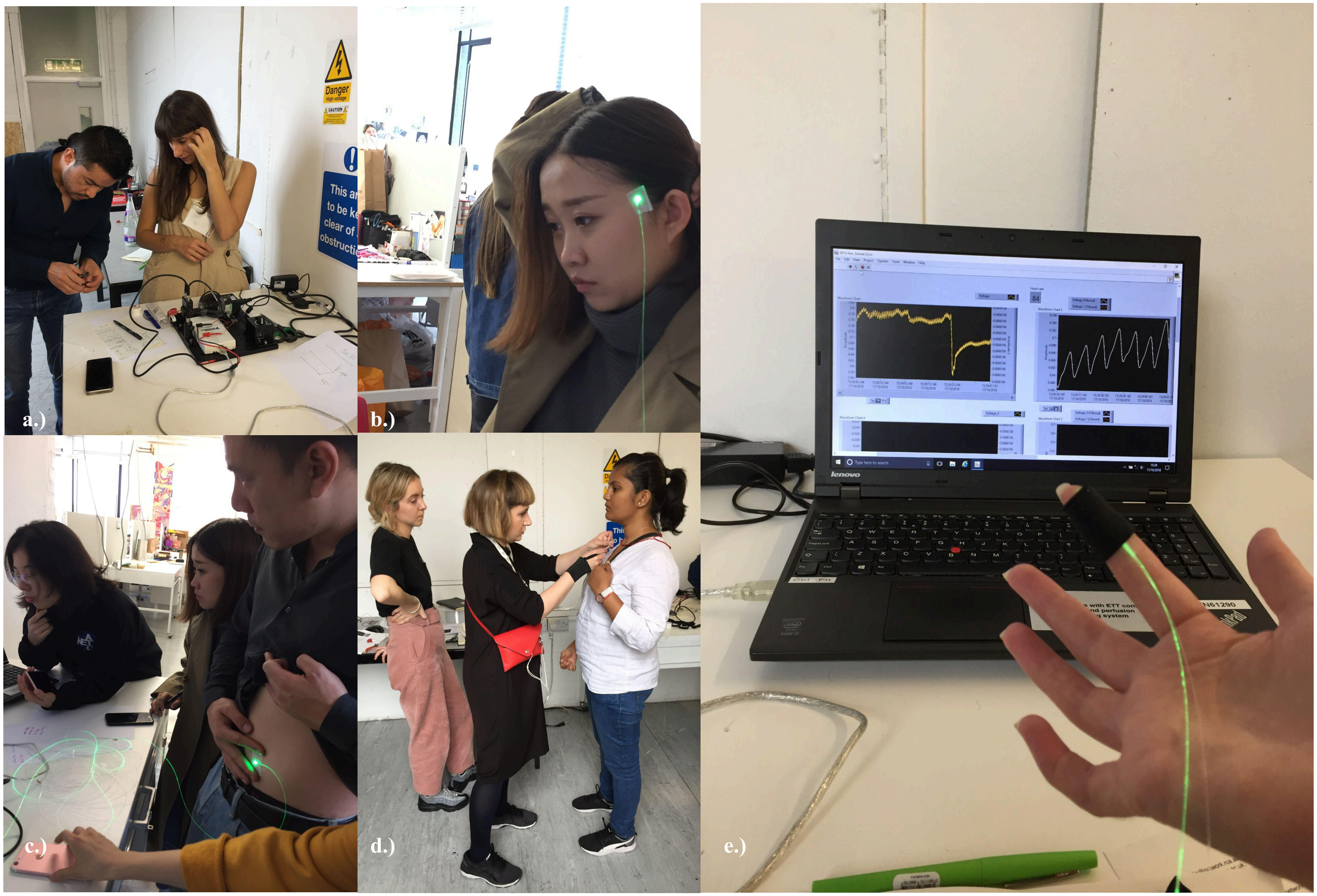

Figure 4.2. *Investigating the functionality and placement of POF as OFS during the workshop using FHL, proprietary software: a) A scientific project contributor demonstrates the sensing capabilities of POFs. b-d) Exploring reading points: temple, abdomen, chest e.) Stabilising the fibre at the fingertip for reliable data visualisation.*

The technical and practical insights gained from different approaches (referred to as 'know-how', 'know-with' and 'know-what') were distilled into a set of design considerations that I brought into the sampling process (Table 4.1). Collectively, the purpose of these considerations was to strike a harmonious balance between adequate technical proficiency and appealing sensory and tactile features within the samples.

Table 4.1. Design considerations informing the sampling process for developing knitted wearable photonic textiles

Material Category	Design Considerations
Fabric	- **Considerations:** - Colours (to conceal the OFS) - Thermoregulatory properties - Sustainability impact - Washability - **Integrated/Designed-In Features:** - 'Reading points', where the OFS will need to be held against the skin in an optimal on-body location - Gaps of 1-2 mm between coupled fibres that must be maintained - Positive sensory qualities (i.e., texture, handle, drape and appearance)
Optical Fibre	- OFS must be stabilised within textile structure, preventing relative motion between fibres, yarns and skin to ensure reliable readings - The measured light intensity will change if the fibre moves within the textile structure or on the skin (diminishing the intensity of light absorbed by the tissue and thus impeding reliable monitoring of physiological data-sensing using POFs) - To facilitate both input and output (i.e., transmitting and receiving light), two fibres must be run alongside one another in a process called 'coupling'. These coupled fibres work best with a gap of approximately 1–2 mm gap between them - For PPG readings, the tips of coupled optical fibres must be exposed and held securely against the reading position on the skin, on a part of the body at which the blood vessels are more accessible (e.g. the wrist) - Cleaving the fibres at a 45-degree angle will allow the reflection of more light into the tissue and therefore back into the fibre

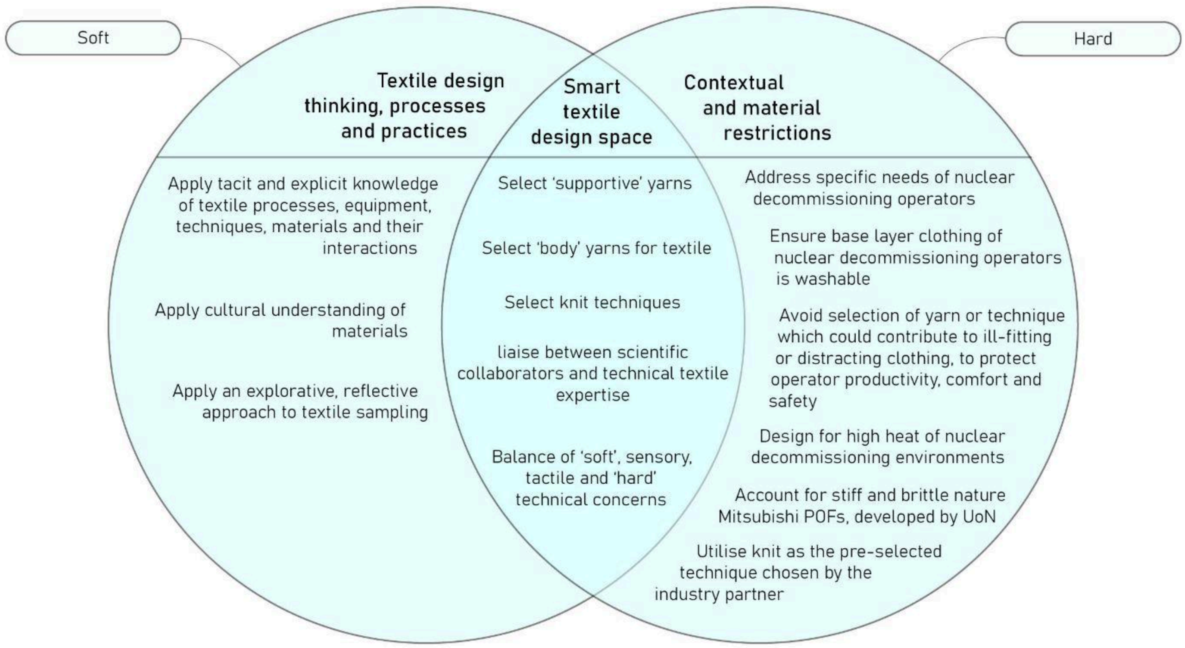

Figure 4.3. *The project spaces in which I operated as a smart textiles designer.*

Figure 4.3 illustrates where these considerations are positioned within the respective 'hard' and 'soft' project domains. The 'hard' domain includes material constraints relating to the specific ways in which OFS must be positioned within a knitted textile to function effectively. Similarly, although the scientific literature notes that POFs are similar to textile fibres and therefore can be processed in the same way,[251] they are perceived as stiff and brittle as well as possessing additional, previously unfamiliar technical properties (Appendix B). This therefore makes them a 'hard' consideration. The highly specific context of nuclear decommissioning, including the need for operator base layers capable of withstanding high temperatures, also falls into the 'hard' category. Meanwhile, the 'soft' domain encompasses textile design expertise, including a knowledge of materials and structure, thought processes, methodologies and practices. I had to interweave technical and sensory concerns through my choice of technique, yarns, and structures to create outcomes that would be comfortable and appealing, as well as washable and technically functional. To support this, I embraced my metaphorical research identity as a material explorer, a role that allowed me to approach this new territory with curiosity and creativity.

[251] Stepan Gorgutsa, Joanna Berzowska, and Maksim Skorobogatiy, 'Optical Fibres for Smart Photonic Textiles', in *Multidisciplinary Know-How for Smart-Textiles Developers*, ed. by Tunde Kirstein (The Textile Institute, Woodhead Publishing in Textiles: Number 139, 2013), pp. 70–91.

4.2.1. A Textile design approach towards the selection of materials and techniques

Building on the knowledge gained from the literature review (Appendix B) and within the workshop (Appendix C) and with technical support provided by Gary Parker, Specialist Technical Instructor in Knit at the RCA, I designed and developed a series of 16 knitted textile samples, using the RCA's on-site textile design workshops on an industrial flat-bed knitting machine (see Appendix D). The design approach taken toward the fabric developments focused on three key areas of technical concern which, although presented sequentially, were often explored simultaneously (see Figure 4.5) due to their interrelated nature:

1. Integrating POFs into knitted textiles;
2. Stabilising POFs to limit movement;
3. Establishing effective reading points.

My selection of materials (Table 4.2) and techniques (Table 4.3) was primarily driven by these technical requirements to ensure sensor functionality and data reliability. However, I also emphasised 'softness' and considered the sensory and tactile attributes of the materials and techniques to align the samples with both their intended application and the broader aims of my research. To reconcile these requirements during design and development, I made incremental adjustments and refinements during sampling, based on feedback gained through physical handling and observation. This allowed me to address the multiple design considerations (see Table 4.1) simultaneously, while maintaining a flexibility in response to emerging insights.

Table 4.2. Materials selection rationale

Material Component	Material type	Rationale
Optical Fibre	Polymeric optical fibre made from Polymethyl Methacrylate (PMMA)	- Sensing capability - Commercial availability - Length and consistency for industrial scale use - Placeholder for UoN OAP's in-development OFS
Yarns	Merino wool	- Inherent thermoregulatory properties - Handfeel - Wickability - Various colours including creams for the 'body' yarn and high contrast colours as visual indicator of the intended path of POF - Compatibility with equipment
	Moisture management enhanced performance merinos	- Moisture-wicking yarns to reduce perspiration-caused fibre slippage, which can reduce the reliability of readings - Compatibility with equipment
	Thermoplastic speciality nylon	- 'Supportive' yarn to prevent POF sliding, 'fix' in

Material Component	Material type	Rationale
	yarns	place through heat processing - Compatibility with equipment
	Heat-activated shrink yarn	- 'Supportive' yarn to prevent POF sliding by shrinking stitches around it - Compatibility with equipment

Table 4.3. Technique selection rationale

Main objectives being explored	Rationale	Techniques/approach	Sample nos.
Integration of OFS	To integrate in a way that ensures its effective functionality (the transmission of light signals)	Inlay in knitted double-bed 1x1 rib	1-16
Stabilising and securing OFS within the structure	To prevent lateral movement of the OFS within the textile structure to ensure precise and reliable data measurement	Steam-shrinking and securing stitches	6-9
		Adjusting quantities of heat-fusible yarns	10-16
		Inlaying bulky yarn alongside inlaid POFs	15-16
Reading points	Establish 'designed-in' points in the textile where the physiological data can be captured	Modified textile from double- to single-bed at designed intervals	10-16
Minimising fibre kinking and damage	Preventing OFS from bending, kinking and damage is fundamental to their effective use	Adjusting structures and yarn combinations responsively throughout sampling	1-16
Maintaining handfeel, drape and appearance	Contribute to the comfort and wearability of wearable photonic smart textiles	Adjusting structures and yarn combinations responsively throughout sampling	1-16

4.2.1.1. Selection of materials

The design approach relied on targeted material choices (Table 4.2) including the OFS, which was an 'off-the shelf' unsheathed optical fibre (0.25–mm diameter) made from Polymethyl Methacrylate (PMMA)[252] and used in combination with various other yarns (see Appendix D). These comprised a range of 'base yarns' including 'cashwools,'[253] fine and performance-enhanced merinos and 'supportive', heat-fusible and heat-shrinkable nylon yarns. These were selected owing to their ability to satisfy both the technical demands and my sensory and tactile aspirations for the samples. For instance, my selection of cashwools, for the 'body' of the samples stemmed not only from its naturally thermoregulatory and hypoallergenic qualities but also from its soft handfeel, which is crucial for wearer comfort in high-stress environments. Figure 4.3 shows Sample 13, knitted in cashwool, folded and draped to highlight its softness and flexibility. However, this choice also reflected my tacit understanding of the cultural

[252] This POF was selected as a placeholder for the UoN OAP's in-development OFS, because it was commercially available—being supplied by Universal Fibre Optics and manufactured by Mitsubishi—and therefore available in lengths and consistency required for sampling on an industrial knitting machine.
[253] Thus called owing to their likeness to the fineness and softness of cashmere.

perceptions associated with materials.[254] By choosing a natural fibre, I was intentionally moving away from the synthetic feel of the POF and towards my aim of creating a textile that the wearer would find comfortable and appealing. I also experimented with the incorporation of additional merino yarns that had been treated to possess enhanced moisture-wicking properties in the rows surrounding the OFS; these are faintly visible in Figure 4.5a, highlighting the subtle nature of some critical design decisions. This decision responded to an insight (gained from a scientific contributor) about the need to manage perspiration to prevent OFS slippage against the skin, potentially jeopardising reliable data collection.

Figure 4.4. *Sample 13 folded and draped to highlight its soft, flexible handle and drape.*

[254] O'Connor, 'How Smart Is Smart? T-Shirts, Wellness, and the Way People Feel about "Medical" Textiles'.

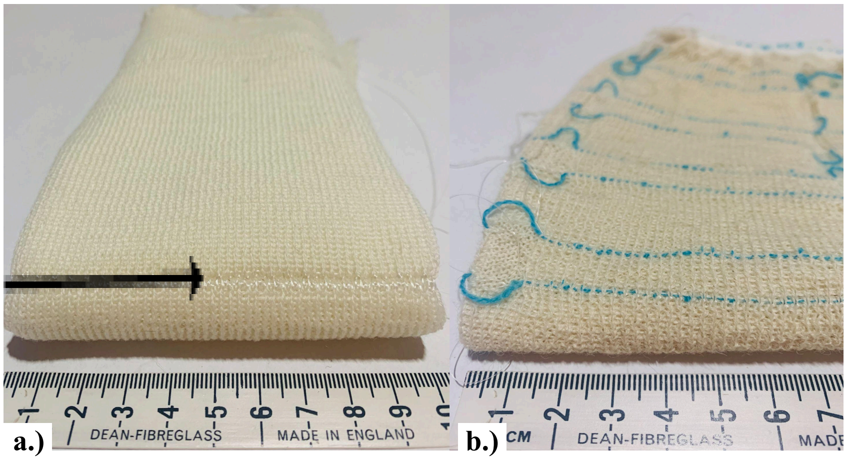

Figure 4.5. *Implementing critical design attributes through targeted yarn placement. a) The arrow indicates faintly visible additional enhanced moisture-wicking merino yarns incorporated into the rows surrounding the inlaid POFs in Sample 6. b) The introduction of a blue-coloured yarn serves as an informational design feature, highlighting the yarn path in Sample 2.*

My colour choices were also carefully considered and were technically strategic with regard to sensory experience. I decided on a limited palette of whites and creams, as this not only contributed to a cleaner look but also simplified my considerations during the project's initial stages. I imagined that these samples could either function as a visually cohesive early-stage collection on their own or could be further developed with colour exploration in a later phase were the project to continue. Our visual experience of colour is often 'bound up' with our sensory experiences of tastes, textures and smells.[255] Therefore, I introduced colour sparingly, incorporating it in only a few instances (see Figure 4.5b), when it served as an informational design feature to highlight a yarn path. However, my decision not to further explore colour also demonstrates my prioritisation of technical investigations over sensory/aesthetic exploration. I made this choice to conserve mental energy, because I found it challenging to navigate between the two realms. By embracing my material explorer identity, I reframed any sense of compromise as an essential step on the journey toward my ultimate end point of bridging the gap between sensory experience and technical functional integration in wearable smart textiles.

4.2.1.2. Integrating POFs into knitted textiles

A key focus of this project was on integrating the OFS into the fabric in a way that ensured functionality (i.e. transmitting and receiving light signals), while simultaneously ensuring it remained in place. Insights from the literature review indicated that 'inlay', as depicted in Figure 4.6a (see Appendix B) was the only viable method for integrating OFS into knitted textiles. Using inlay enables the integration of POF in a continuous serpentine form, as depicted in Figure 4.6b 'without any bending or significant undulation,' thereby reducing potential damage, preventing breakage and facilitating its use as a sensor.[256]

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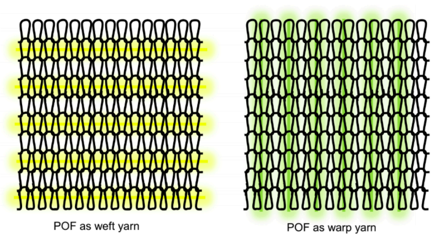
[255] Philpott, 'Structural Textiles: Adaptable Form and Surface in Three Dimensions', p. 77.

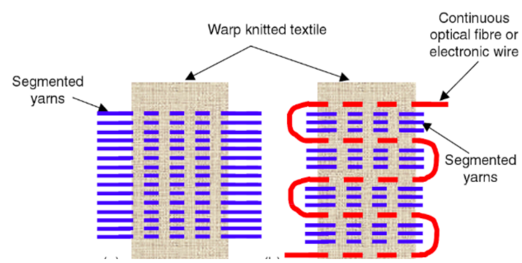
[256] Viktoria Schrank and others, 'Polymer-Optical Fibre (POF) Integration into Textile Fabric Structures', in *Polymer Optical Fibres: Fibre Types, Materials, Fabrication, Characterisation and Applications*, ed. by Christian-Alexander Bunge, Markus Beckers, and Thomas Gries, Woodhead Publishing Series in Electronic and Optical Materials, number 89 (Woodhead Publishing is an imprint of Elsevier, 2017), pp. 337–48.

Positioning the OFS centrally within a double-bed knitted structure, as can be achieved with inlay (Figure 4.6), effectively conceals it from both touch and sight, as shown in Figure 4.6a. Consequently, I chose the 'inlay' method for most of the samples.[257] However, while horizontal inlay effectively concealed the fibres, it also impacted the flexibility and drape of the textile given the inherent stiffness of the OFS. This compromise illustrates a point of conflict between technical functionality and sensory design priorities, where fabric handle and drape were impacted to accommodate technical requirements. These constraints would inevitably place design constraints on the garment[258]

Balancing these competing priorities demonstrates how I navigated the trade-offs between maintaining technical functionality and preserving sensory qualities like drape and handle. Initial attempts to inlay the POFs into the knitted textile resulted in the fibres kinking and becoming damaged. This prompted an adjustment to the positioning of the spool from the top of the machine to the floor behind it to prevent the OFS from catching on the spool's rim during entry into the machine (see Figure 4.7).[259] These changes were necessary due to the lack of a dedicated yarn track for feeding stiff or low-elongation yarns into the machine.



a.)



b.)

Figure 4.6 *Integrating Optical fibres into knitted textiles a) Integrated via inlay into weft knitted textiles as either a weft (left) or warp yarn (right). In: Viktoria Shrank and others, 'Polymer-Optical Fibre (POF) Integration into Textile Fabric Structures', in Polymer Optical Fibres: Fibre Types, Materials, Fabrication, Characterisation and Applications, ed. by Christian-Alexander Bunge, Markus Beckers, and Thomas Gries, Woodhead Publishing Series in Electronic and Optical Materials, 89 (Elsevier, 2017), pp. 337–48. b) Schematic diagram showing two approaches to integrating POF into knitted textiles either segmenting yarns or via a continuous serpentine shape. The degree of loop should not go below the minimum bend radius of the POF. In: Shrank and others, 'Polymer-Optical Fibre (POF) Integration into Textile Fabric Structures'.*

[257] Inlay was used for samples: 1—3 & 5—16. It was not used on Samples 4 and 5, when a knit-weave technique was temporarily explored.
[258] Chen and others, 'Challenges in Knitted E-Textiles', DCCCXLIX, p. 131.
[259] The POF was left on large spools because their slippery nature meant that it was not possible to wind them onto smaller cones that could have been placed on top of the machine.

Figure 4.7. *The POF spools were placed on the ground behind the knitting machine and fed directly onto the machine to avoid exerting stress on the fibre.*

4.2.1.3. Stabilising POFs to limit movement

I also attempted to stabilise the OFS within the textile to prevent lateral movement, as shifts within the textile structure could result in inaccurate data measurements.[260] These efforts aimed to support functionality without compromising the fabric's handfeel, which is crucial for wearer comfort. In relation to this, four key approaches involving strategic yarn combinations, structural design and post-processing to hold the POFs, were explored:

1. Incorporating heat-fusible yarns, either alone or combined with soft, wearable yarns, alongside the inlaid OFS or within the surrounding holding stitches, and adjusting their quantities (Samples 1–16);
2. Integrating a heat-shrinkable yarn to tighten/clasp the stitches surrounding the inlaid fibres (Samples 6-9);
3. Inclusion of additional merino yarns to support the heat-fusible yarns as 'scaffolds' (8-12);
4. Inlaying a 'bulky' yarn alongside the OFSs (Samples 15-16).

These approaches highlighted the complexity of working with unconventional fibres, where achieving stability often conflicted with the need for flexibility and softness. Adopting the perspective of 'the material explorer,' helped me to approach these difficulties creatively and to view these constraints as opportunities to explore innovative techniques.

[260] Xuhui Zhang and others, 'Wearable Optical Fiber Sensors in Medical Monitoring Applications: A Review', *Sensors*, 23.15 (2023), p. 6671, doi:10.3390/s23156671.

As outlined in table 4.3. my initial approach to securing and stabilising the OFS involved inlaying the heat-fusible yarn alongside the OFS within a double-bed 1x1 rib structure. The rationale was that once activated, the heat-fusible yarn would prevent OFS movement. Although this method avoided adding rigidity or compromising handfeel, the OFS looped excessively when tension was released on removal from the machine. Tactile assessment also revealed that OFS movement was not inhibited. Improved techniques would be required to address this without sacrificing sensory qualities.

In Samples 4 and 5, I attempted to mitigate the excessive looping and I changed the structure to a single-bed jersey with the intention of mimicking a woven structure in the area the OFS was inlaid, thereby securing the OFS more effectively; here, the idea was that looped-stitches would hold the OFSs in place from either side of their horizontal path. While the OFS appeared less damaged than previous samples (see for instance 4.8a) when removed from the machine (4.8b), this improvement was probably a result of changes in the spool's positioning rather than the structural adjustment itself. Regardless, hands-on manipulation revealed that the OFSs could still slide laterally within the fabric after heat-processing. In addition, the OFS still protruded at the sides and their horizontal placement, combined with the finer weight of the samples, caused the samples to curl (Figure 4.8c).

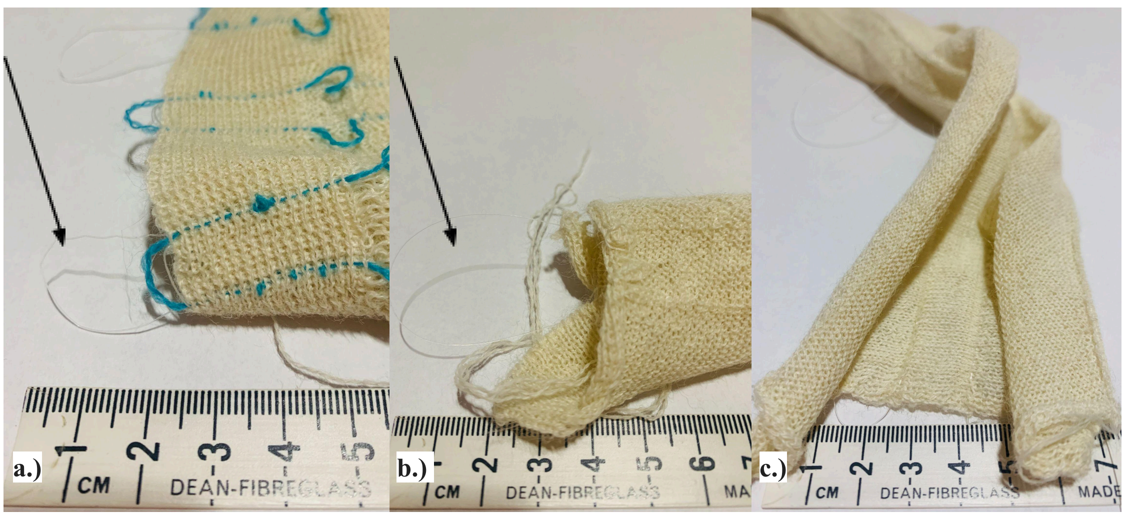


Figure 4.8. *a) Arrow points to kinked and damaged POFs looping out of the side of Sample 2. b.) While arrow points to undamaged POFs loop out at the side Sample 4, a single-bed 1x1 rib sample, the POF was not prevented from sliding laterally within the structure c.) The combination of the single-bed structure and the linear nature of inlay, along with the inlaid POF, caused curling, as seen here in Sample 4.*

Reflecting on these limitations, and aligning with Schön's concept of *'*reflection-*in*-action*,'* I recognised the need to refine my approach and explore alternate techniques, prompting a move towards the introduction of a heat-shrinkable nylon/lycra yarn (Samples 6-9) in the 'holding-stitches' surrounding the inlaid OFS. The rationale was to contract these stitches via steam-shrinking (see video here), thereby causing them to 'grip on to' the OFS and then to secure them via strategically placed heat-processed heat-fusible yarns (acting as an adhesive) coursing through the rows adjacent to the heat-shrink yarns at the reading points.

Physical handling of Sample 7 indicated that although the fabric had shrunk and tightened as expected, heat-processing had not prevented lateral sliding of the OFS. Furthermore, the heat-fusible yarns lacked a core, meaning that they melted during heat processing and failed to interloop with neighbouring stitches (Figure 4.9). This loss of structural integrity meant that the POFs were not securely held in place compromising technical functionality. Furthermore, tactile assessment revealed that these areas exhibited a crispy and 'plasticky' texture, detracting from the sensory qualities of the samples.

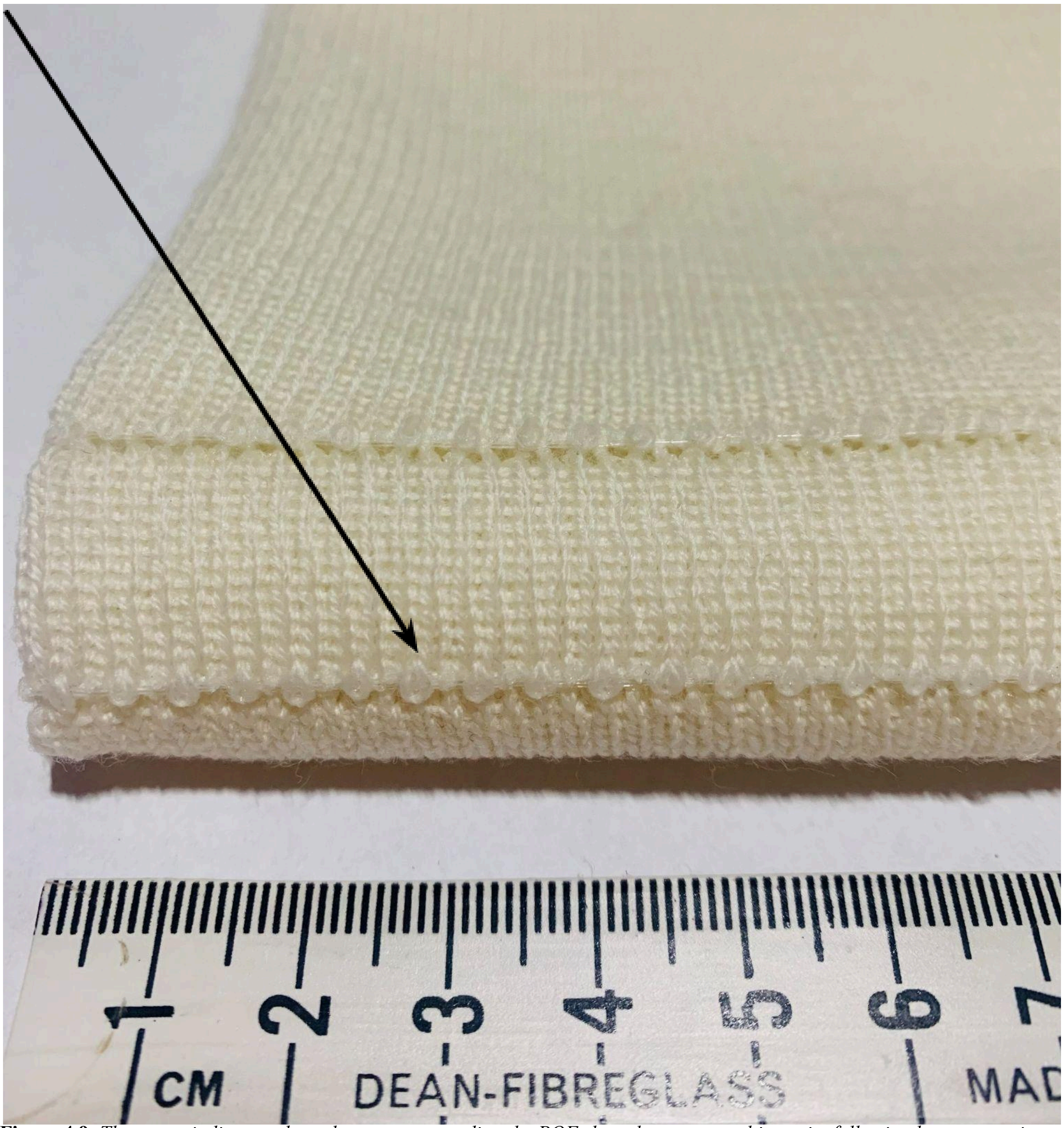


Figure 4.9. *The arrow indicates where the rows surrounding the POFs have lost structural integrity following heat processing. This comprises the fabric's technical functionality and results in undesirable tactile qualities, characterised by 'crispy' and 'plasticky' textures.*

To address these challenges, I gradually incorporated additional merino yarns into Samples 8 and 9 as fibrous scaffolding for the heat-fusible fibers to prevent degradation. However, haptic evaluation revealed ongoing rigidity in these areas, further demonstrating the tension between stabilising fibres and ensuring an appealing fabric handle. In addition, the increased number of yarns coursing through rows adjacent to the inlaid OFS made the fabric denser in those areas and this caused rippling across the fabric (see Figure 4.10a). Furthermore, OFS movement persisted, highlighting the need for continued exploration.

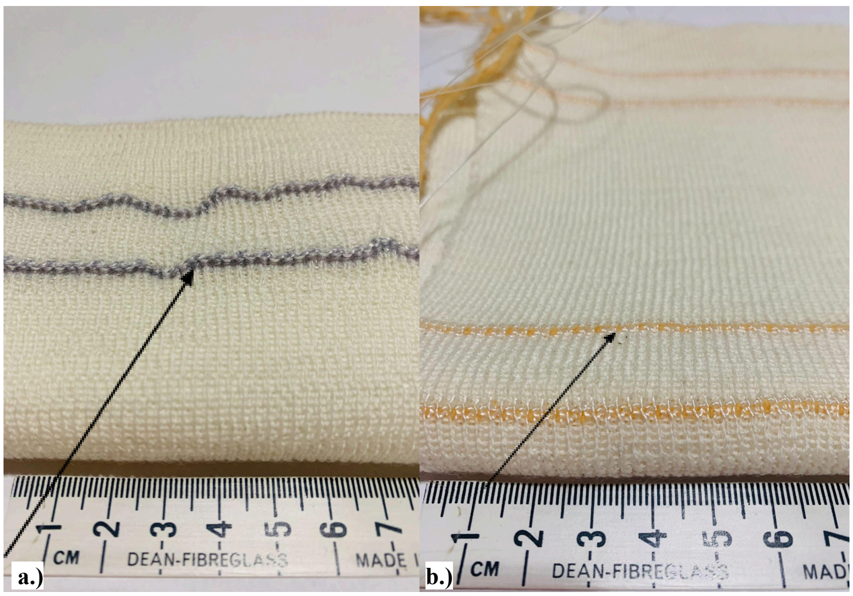


Figure 4.10. *Incorporation of additional merino yarns to enhance fabric softness and stabilise POFs. a.) The arrow indicates the incorporation of additional grey merino yarns in the rows adjacent to the inlaid POFs in Sample 9, which resulted in uneven fabric density and rippling. b.) The arrow highlights the use of a thicker, orange merino yarn in Sample 15, inlaid alongside the POFs and heat-fusible yarn to inhibit POF movement within the structure.*

To address the rigidity and the ongoing issues of OFS looping out of the textiles, I replaced the nylon/Lycra yarn with an additional merino yarn in Sample 10. However, this adjustment did not resolve the issue of OFS movement, and the additional yarn contributed to further fabric rippling. Excessive fabric rippling could compromise the accuracy and reliability of physiological measurements by having an unpredictable impact on OFS alignment and positioning. Moreover, ripples in a base layer garment could cause wearer discomfort, as uneven fabric surfaces might result in irritation or chafing during motion. I therefore removed the additional merino yarn, which resulted in improved OFS stability in Samples 13 and 14.

To further reduce the lateral movement of the OFS, Samples 15 and 16 built on prior observations regarding the interaction between the ‘slippery’ OFS, the heat-fusible yarn and the merino yarns—where the merino yarns acted as a fibrous scaffold to support adhesion of the heat-fusible yarn. Here, I inlaid a thicker, bulkier merino yarn alongside a heat-fusible yarn and the OFS, effectively ‘filling the gap’ surrounding the OFS and preventing its movement within the structure (see Figure 4.10b). This method represented a promising resolution to the trade-offs between stabilising the OFSs without overly compromising the fabric's tactile qualities.

4.2.1.4. Establishing reading points

I established reading points for accurate biometric data collection within the knitted textile structures that aligned with the parameters defined for effective use of OFS in wearable physiological monitoring (see Figure 4.11). These reading points were conceptualised at the initial stages of sampling and subsequently became a 'designed-in' feature in evolving designs.

I considered both the technical requirements of using POF as OFS (see Appendix B) and my sensory and tactile design priorities. As mentioned (p.72) inlay enabled me to embed the yarns within the knitted structure, and I modified the knit structure from a double- to a single-bed structure only at the designed exposure points ('reading points'). This ensured that the OFS remained concealed within the textile except at these critical areas, where the inlayed coupled fibres were exposed and would be cut, thereby allowing for a more seamlessly integrated sample.

Although precise measurements of the intervals between reading points were not a primary concern at this stage, because the samples were not yet designed for specific areas of the body, the intention was to refine these details in subsequent development phases, should the project have progressed further. I pursued all three technical areas simultaneously to ensure compatibility between techniques and to avoid redundancy in developments. This approach allowed for gradual improvements and the creation of a softer, more flexible fabric over time.

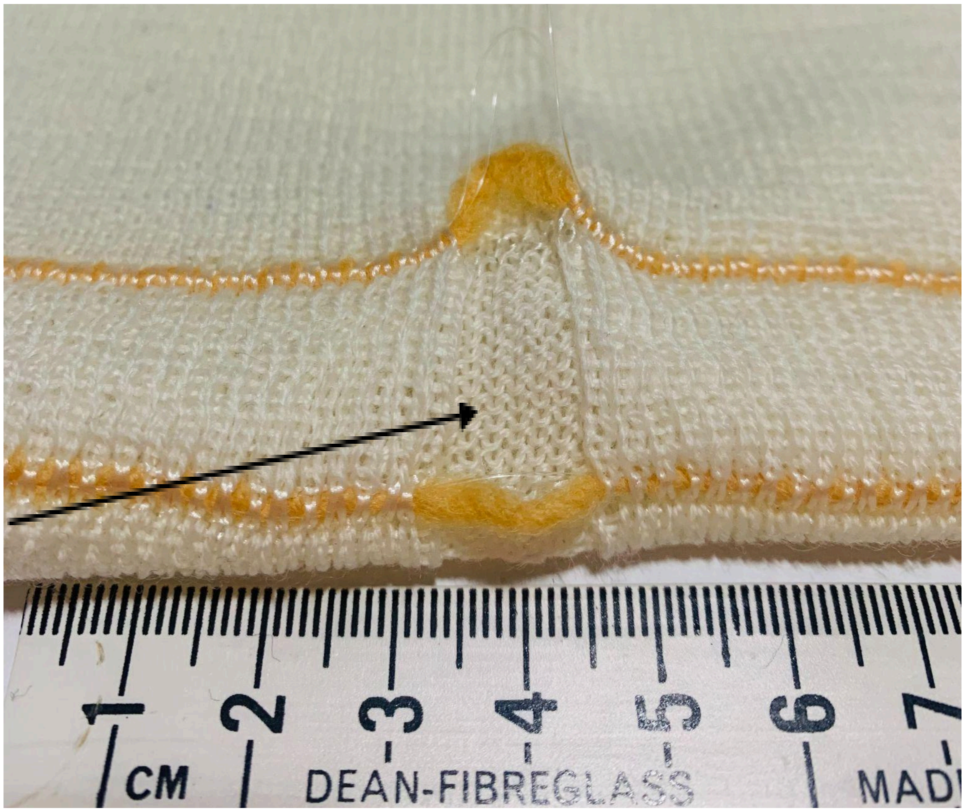


Figure 4.11. *Detail of the sample with the reading point (skin-facing side) of Sample 16 visible in the centre of the image and indicated by an a. It is at this point that the coupled fibres would be cut.*

4.3. Analysis and opportunities for future research

Designing and developing early-stage wearable photonic textile samples has served as a gateway to analysing the approaches and conditions surrounding their production. The findings are grounded in reflective analysis of the making process and its active documentation through photography, sketches and diagrams.[261] I have also drawn on my personal experiences of interdisciplinary engagement during their production.[262]

The project's primary goal was to explore the feasibility of a wearable photonic textile integrated system as a valid option for enhancing operator productivity and comfort during nuclear decommissioning operations. My role as the key research associate from textile design perspective was to develop a series of knitted textile samples incorporating POFs as OFS, addressing both technical functionality and the sensory and tactile requirements of a base-layer inner-suit garment. Key considerations included effective

[261] Schön, *The Reflective Practitioner*; de Freitas, 'Towards a Definition of Studio Documentation: Working Tool and Transparent Record'.

[262] Jean Dorothy Clandinin and Frank Michael Connelly, 'Personal Experience Methods', in *Handbook of Qualitative Research*, ed. by Norman K Denzin and Yvonna S Lincoln (Sage Publications, Inc., 1994), pp. 413–27.

integration and stabilisation of OFSs, developing reading points and minimising damage through kinking. Critical design attributes such as handle, drape, texture, and moisture management were also prioritised.

The main conclusions from the development of these early-stage samples (Appendix G) include the technical feasibility of integrating POFs as OFSs into knitted textiles intended as base-layer inner-suit garments (see particularly, Samples 14—16; Figure 4.10b and 4.11). This demonstrates the importance of working across disciplines while highlighting how textile design has enriched the smart textile development process by addressing both technical and wearer-centred considerations. Although progress was made toward balancing technical functionality with sensory qualities, further refinement is needed to achieve an optimal balance. The sampling process revealed the nuanced and interrelated nature of development decisions. Addressing one area often created new challenges in another, underscoring the need for holistic smart textile development and the value of my reflective, experiential approach in refining techniques.

Although immediate functionality was not the primary focus, I identified promising technique and yarn combinations for potential quantitative testing by scientific researchers in subsequent stages. As discussed, performance-enhanced, high-wicking merino yarns were strategically placed near reading points to wick sweat away from the body and ensure accurate biometric readings by minimising fiber slippage against the skin. However, without quantitative testing aligned with the intended application (planned for the competition's second phase; see Appendix J), further exploration was paused to avoid redundancy (i.e., developing a textile that was sensorially pleasing but lacking technical functionality). Nevertheless, these efforts established a foundational understanding of the challenges and opportunities of integrating POFs as OFSs into knitted textiles.

Samples 14—16 were the most successful in terms of balancing functional and design considerations and notably, Samples 15 and 16, demonstrated the feasibility of using OFSs for wearable monitoring in base-layer inner-suit textiles. Promising avenues for future development include refining the techniques employed in these samples with a finer-gauge knitting machine and expanding sensory exploration to further enhance comfort and wearability. In addition, exploring alternate knitting processes, such as seamless warp knitting,[263] which allows for vertical yarn inlay and thus a modified fabric drape, could optimise fiber orientation and fabric structure for improved wearability as well as enabling simultaneous considerations of fibre physical properties with both textile structure and garment construction methods. In conclusion, although challenges persist in integrating POFs as OFSs into knitted textiles, the potential benefits of achieving comfortable and sensorially pleasing on-body monitoring are considerable, making further development well worth pursuing. This work highlights how I developed and applied a deeper understanding of working with POFs in knitted textiles for use as OFSs, illustrating the crucial role of textile design expertise in advancing wearable smart textiles through interdisciplinary engagement.

[263] Subhankar Maity, Kunal Singha, and Pintu Pandit, ‘Production of Seamless Knitted Apparels’, in *Advanced Knitting Technology* (Elsevier, 2022), pp. 203–18, doi:10.1016/B978-0-323-85534-1.00012-X.

4.3.1. Approach to practice

The practice presented in this study emphasises a 'soft' reflective and hands-on approach towards incorporating POF as OFS in knitted textiles. The samples rely on the combined use of the industrial knit machine and commercially available materials.

During sampling, I made decisions regarding the selection of techniques and yarns that could address both technical functionality and sensory experience. I had hoped to incorporate the POF into knitted textile structures without compromising the sensory qualities of the sample or the tactile experience that they offered. However, the technical objectives (4.1.1) took precedence, and this highlights how the 'hard' context influenced my approach, it was only by addressing these project objectives that I could begin to address my 'soft' concerns.

Alongside the three key areas of technical focus (see p.71), continuous and ongoing considerations included (a) minimising OFS damage, which occurred primarily via kinking during sampling and wear, and (b) instilling positive fabric texture, handfeel and drape, important for comfort and wearability of fabrics intended to be worn for extended periods of time. I directly built on insights gained from scientific researchers during the workshop by strategically placing performance-enhanced merinos at 'designed-in' reading points to wick perspiration away from the surface of the skin. This aimed to prevent fibre slippage and improve sensor accuracy. I developed several samples for further development (in particular Samples 14-16); these built on the use of the inlay technique by incorporating 'supportive' heat-fusible and 'bulky' merino yarns alongside the POF to secure it for its use as a wearable sensor. These were combined with soft, wearable merino yarns widely used in the fashion and textile industry with integrated moisture-management and thermoregulatory properties (Appendix D).

The sampling process required that I consider these multiple areas simultaneously, rather than focusing on one area more fully. Owing to the interrelated nature of knitted textile sampling, a change made to one area, such as fibre type, yarn combination or structure, impacts another and can significantly alter the resulting quality of the textile. This demonstrates the complexity of balancing technical, sensory and tactile qualities in smart textile design and how choices and refinements made during sampling require a nuanced, experiential approach (see for instance Anindya Ghosh and others).[264] For instance, when I introduced the nylon/lycra heat-shrink yarns (Samples 6), the fabric shrank, resulting in excessive looping and subsequently damage to the fibre (Figure 4.8a). This required adjustments in subsequent samples. In Sample 9, the inclusion of a thicker merino caused rippling within the fabric (Figure 4.10a). The reflective, processual and tacit nature of the adjustments that were made throughout, align with Schon's[265] notion of reflection-*on* action and can also be seen in the hands-on, experiential methods I employed when:

[264] Anindya Ghosh and others, 'Analysis of Knitting Process Variables and Yarn Count Influencing the Thermo-Physiological Comfort Properties of Single Jersey and Rib Fabrics', *Journal of The Institution of Engineers (India): Series E*, 97.2 (2016), pp. 89–98, doi:10.1007/s40034-016-0079-3.
[265] Schön, *The Reflective Practitioner*.

- Haptically assessing the textiles' weight drape, and surface quality right off the machine;
- Wrapping the samples around the curve of my wrist to uncover critical insights into their conformability and drape, observing whether or not the fabric had the flexibility necessary for an inner-suit garment;
- Ensuring that the POFs felt secure without compromising comfort;
- Recognising potential improvements, such as subsequently moving to a finer-gauge knitting machine, a resource that was unavailable at the RCA.

These examples highlight the challenge of balancing multiple priorities and emphasise the important role of responsive adjustments, continuous reflection-*in* action and tacit knowledge during the sampling process. My textile design expertise has largely been applied within the tactile domain and has enhanced comfort and wearability, as well as demonstrating the value of tactile engagement. For instance, the choice of a merino wool over a coarser wool was crucial in avoiding the discomfort commonly associated with the 'prickle' sensation.[266] However, the intangible aspects of my expertise have also played a vital role beyond the tactile realm. My past experiences of working with heat-fusible yarns, engaging with multiple disciplines, and working with knitted textile technologists have probably also added depth to the sampling process by means of the familiarity and ease of working with the materials that I brought to this project; such elements, however, are difficult to substantiate.

These early-stage developments underscore the value of textile design approaches within this domain, because their very existence is testament to the success of my approach. Specifically, my hands-on making skills, coupled with access to essential resources, including equipment and expertise, have significantly advanced the project. Furthermore, my exploration as a textile designer represents a novel contribution by highlighting the unique value of incorporating textile design expertise to navigate and integrate multiple factors in the wearable smart textile design and development process.

4.3.2. Navigating roles and learning modes

Where diverse disciplines converge, there is a distinct need to effectively bridge gaps in knowledge and practice. To create the samples, I served as a vital link that connected various stakeholders, from scientific partners and students to textile experts at the RCA. This position required significant adaptability and effort on my part, as I was obliged to translate the materials' intrinsic value and functionality across disciplines, while simultaneously deepening my own knowledge about the use of POFs in textiles and attempting to skilfully navigate a range of conflicting attitudes towards POFs. This task often entailed balancing the enthusiasm of POF developers with the less-than-excited attitude of the technical textile experts who found the POFs 'horrid to work with', 'difficult', and 'fragile', and who noted that they had 'zero tolerance to anything'.

[266] Apurba Das and R. Alagirusamy, 'Neurophysiological Processes in Clothing Comfort', in *Science in Clothing Comfort* (Woodhead Publishing India PVT Ltd, 2010), pp. 31–53 (p. 37), doi:10.1533/9780857092830.

I adopted a multifaceted approach to the requisite knowledge acquisition for working with POFs as OFS in knitted textiles. This approach encompassed knitted textile sampling, which allowed me to lean into my role as a 'maker', drawing on my 'know-how' learning mode and emphasising both practical and tacit knowledge construction methods. I also conducted desk-based research, preparing a literature review to assess the current state of the art, utilising the 'know-what' learning mode. In parallel, I designed, led and actively participated in a workshop in which I assumed multiple roles, from facilitator to co-researcher, applying both 'know-how' and 'know-with' learning modes. When taken together these processes demonstrate the fullness of the textile design approach that I adopted. A summary of the roles, methods, tasks and responsibilities of textile design within the case study and their associated learning modes is provided in Appendix I.

The project's demands required an ability to fluidly navigate between these varied roles and learning modes. Figure 4.12 offers a temporal perspective on this, tracing these roles across the project's three-month timeline. At times, the roles overlapped and they were also mutually interdependent, as my role as a maker relied on insights from the literature review and hands-on experiences gained during the workshop. Likewise, my experience as a maker supported findings from the literature review. This blending of roles and synthesis of material knowledge gained from various learning modes supported the creation of the physical samples by ensuring an approach that was both targeted and holistic. Such an approach has proven useful in working on a time-constrained material development project, wherein access to equipment and technical support may be both difficult to secure and costly.

During the knitted textile design sampling process, I transformed rigid sensor functionalities into soft, wearable outcomes. To achieve this, I 'translated' [267] insights and experiences gained during the project's early stages and refined them into knitted smart textile samples. Figure 4.12 highlights how I compartmentalised this journey of material knowledge generation and sampling into three distinct segments, gather, transform and distil, thus offering an overview of the constituent elements and stages of the smart textiles design process in this case study. While textile designers typically 'translate' tactile and visual information into fabric, now I have translated technical and tacit information obtained from both scientific literature and direct material engagement.

Finally, central to my journey was my identity as 'material explorer.' Embracing this identity allowed me to foster an exploratory mindset and enabled me to manage my various roles while navigating the challenges inherent in shifting between different and unfamiliar learning modes. This was essential for operating across disciplinary boundaries within the smart textile domain. By embracing the exploratory nature of the work, I have been able to shift between functional and technical constraints and uncover subtle opportunities to enhance sensory and tactile properties. By encouraging a creative outlook, I was able to remain open to unexpected findings that arose during the sampling process. For example, the success of Samples 15 and 16 came from progressive refinements of techniques such as inlaying thicker yarns to stabilise the POFs. Such insights emerged only after observing the changes distinct to the earlier samples. This approach to practice demonstrates the unique value of textile design expertise when balancing multiple considerations in the wearable smart textile design and developments process.

[267] Igoe, 'In Textasis: Matrixial Narratives of Textile Design'.

This mindset of a 'material explorer' helped me to balance the technical and creative aspects of my research by highlighting my role as a creative practitioner and researcher, and working to reveal the space for sensory/aesthetic knowledge in these domains. This approach highlighted how the project's technical constraints and challenges drove my imaginative thinking, aligning with the observations of design researchers,[268] who noted that technically limiting briefs can stimulate creativity by providing a scaffold for creative development.

[268] Philpott, 'Structural Textiles: Adaptable Form and Surface in Three Dimensions'; Jane Graves, 'Symbol, Pattern and the Unconscious: The Search for Meaning', in *Disentangling Textiles: Techniques for the Study of Designed Objects*, ed. by Mary Schoeser and Christine Boydell (Middlesex Univ. Press, 2002).

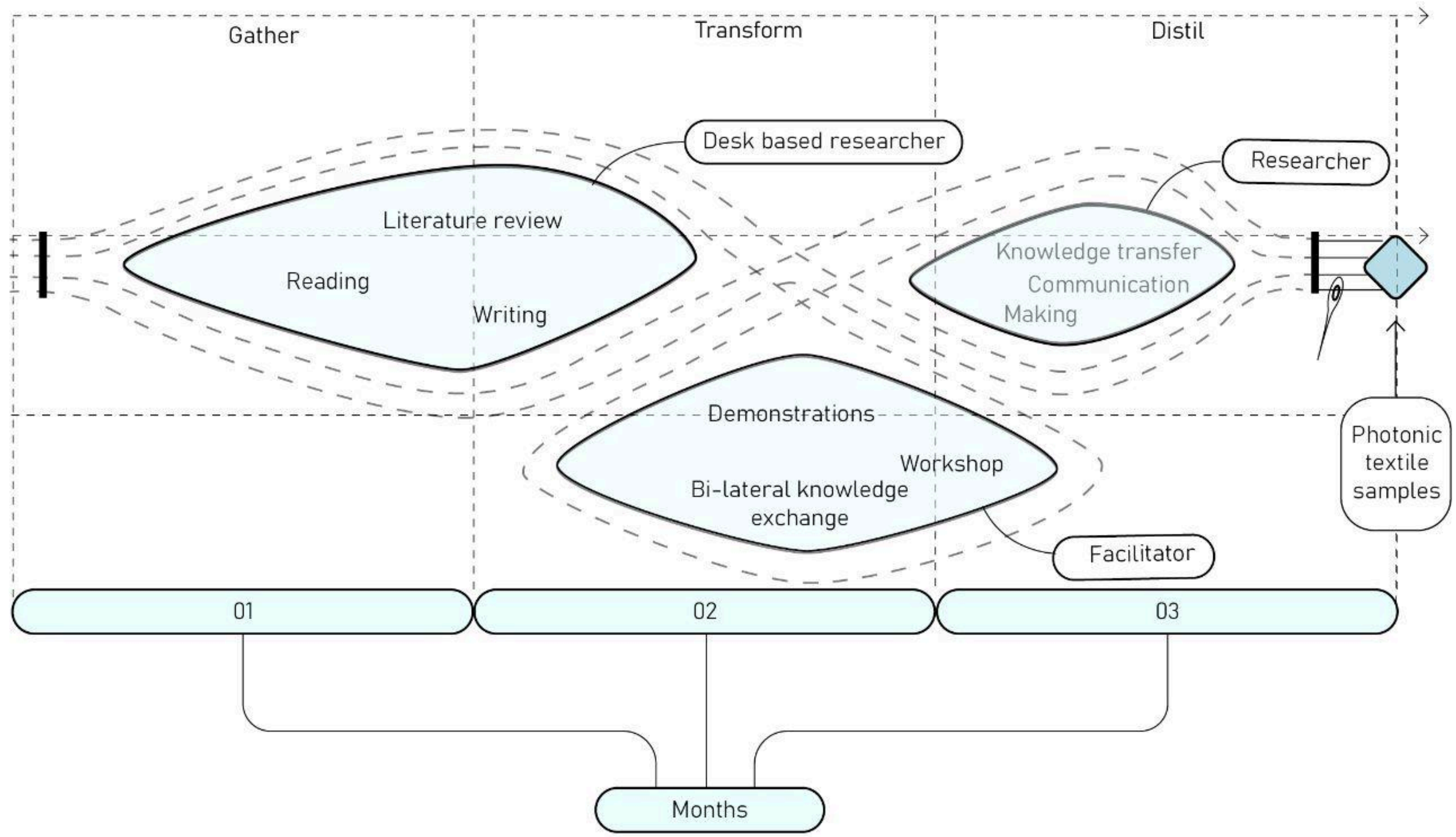


Figure 4.12 *The key roles undertaken during the textile design research process.*

4.3.3. The role of interdisciplinarity

The project's potential for interdisciplinarity was a fundamental driver for my motivation to participate in it. I anticipated at the outset that working within a highly interdisciplinary environment would afford me a better understanding of the potentials of exploratory and experiential materials knowledge within interdisciplinary textile practices. The project exhibits the qualities that are conducive to interdisciplinarity, as identified by Blackwell in Stember's work, which is considered foundational to the field.[269] It focuses on an issue that cannot be addressed by a single discipline; it sits on the 'fringe' of two or more disciplines; and it engages disciplines that appear 'ready and able to collaborate.' However, despite its initial potential and moments of interdisciplinary 'integration', [270] the engagement process aligns more closely with multidisciplinarity.

Klein distinguishes multidisciplinarity from interdisciplinarity by virtue of their varying degrees of 'integration' and 'interaction'.[271] Multidisciplinarity occurs when disciplines are juxtaposed with one another without deep integration of skills and ideas. Many projects that claim to be interdisciplinary adopt what is, in fact, a multidisciplinary approach.[272] Klein explains that in multidisciplinarity, 'juxtaposition' opens up disciplinary practices to a broader range of knowledge and tools while the 'disciplinary elements retain their original identity' and traditional knowledge structures remain unchallenged. In this project, because the disciplines involved retained their original identity, the dominant framework remained rooted in science and engineering. The project's initial design aimed at fostering an interdisciplinary environment, but, after the workshop, when participants returned to their respective laboratories and studios, maintaining the same level of engagement proved challenging. This shift highlighted the tendency to revert to comfortable, familiar ways of working and served as a reminder that intentions and outcomes are not always aligned. The project's organisation and funding sources also reflected the project's basis in science and engineering and the immutability of the POF – developed within these frameworks – is testament to it. My role involved adapting textile design knowledge to fit the contexts of science and engineering, a mode of multidisciplinarity that Boden[273] refers to as 'Contextualising ID'. Leonard and Sensiper[274] have emphasised the crucial role of social interaction in the team development of new products and processes and Cross supports this viewpoint, observing that design processes involving teamwork are inherently social.[275] Social interactions and relationships thus play a fundamental role in projects of this nature, and their importance should not be underestimated. While 'designed interactions', such as workshops, meetings and presentations, facilitated physical gatherings and expanded my textile design horizons, it is my view that their infrequency limited our ability to fully embrace interdisciplinarity.

[269] Marilyn Stember, 'Advancing the Social Sciences through the Interdisciplinary Enterprise', *The Social Science Journal*, 28.1 (1991), pp. 1–14 (p. 6), doi:10.1016/0362-3319(91)90040-B.
[270] Lisa R. Lattuca, *Creating Interdisciplinarity: Interdisciplinary Research and Teaching among College and University Faculty*, Vanderbilt Issues in Higher Education, 1st ed (Vanderbilt University Press, 2001), p. 78.
[271] Julie Thompson Klein, 'A Taxonomy of Interdisciplinarity', in *The Oxford Handbook of Interdisciplinarity*, ed. by Robert Frodeman and others (Oxford University Press, 2010), pp. 15–30 (p. 16).
[272] Julie Thompson Klein, *Interdisciplinarity: History, Theory, and Practice*, 3. print (Wayne State University Press, 1993), p. 56.
[273] Thompson Klein, 'A Taxonomy of Interdisciplinarity', p. 18.
[274] Dorothy Leonard and Sylvia Sensiper, 'The Role of Tacit Knowledge in Group Innovation', 40.3 (1998).
[275] Nigel Cross and Anita Clayburn Cross, 'Observations of Teamwork and Social Processes in Design', *Design Studies*, 16.2 (1995), pp. 143–70, doi:10.1016/0142-694X(94)00007-Z.

The project's short duration and funding limitations, posed challenges to achieving interdisciplinarity, which in turn impacted the depth of engagement possible and affected the project's outcomes, which did not manifest in the ways I intended it to, and even now remain 'unfinished.' An analysis of success solely in terms of design outcomes would be inappropriate, given that the project's main objective was exploration. However, it is nonetheless valuable to understand the barriers to moving beyond multidisciplinarity and the successful further development of photonic textiles. Challenges to interdisciplinarity included:

- Short project duration and funding limitations;
- Limited availability and engagement of scientific project contributors;
- Dominance of science and engineering frameworks in the project structure;

These limitations highlight the boundaries of my engagement. While I remained open and eager to engage with scientific territories, my progress was hampered by factors beyond my control, such as scientific project contributors' unwillingness or inability to engage to the same extent and time and funding constraints. Even with the potential to enhance the samples by drawing on my sensory sensibilities—enhancing their tactile and physical properties through the development of finer, more delicate and comfortable textiles—without feedback on their functional suitability, my efforts risked being redundant or producing sensorially compelling but non-functional samples. I was cognisant that working beyond proof of concept or feasibility would be neither useful to the project at this stage nor of significant interest to scientific project contributors.

Regarding the samples, my inability to further iterate and improve them was evident from the lack of critical feedback from the engineering team and the absence of quantitative analysis. Without this input, I could not assess the efficacy and reliability of the data collection or evaluate the effectiveness of textile design techniques in maintaining OFS positions during wear. These factors could not have been anticipated at the outset. However, it was necessary to take a chance on the project to explore its potential for demonstrating how a textile designer who draws on their experiential and embodied knowledge, can contribute to the design and development of wearable smart textiles through interdisciplinary engagement. My contribution thus felt somewhat limited because my work with the OFS was constrained by technical limitations. Nevertheless, my expertise contributed significantly by transforming theoretical research into tangible photonic textile samples.

Figure 4.13 illustrates my interactions with the project partners. The central line represents both the research timeline and the boundary between textile design and science and engineering. My trajectory through the project is presented as a looping path traversing these domains. The workshop is located just below the central line because while it symbolised an interdisciplinary interaction that was equally beneficial to both sides it was held at the RCA, positioning it closer to the domain of textile design. Through these interactions, I was able to convey my evolving understanding of OFSs to textiles project contributors (monodisciplinary interactions) and build on previous work in the field.

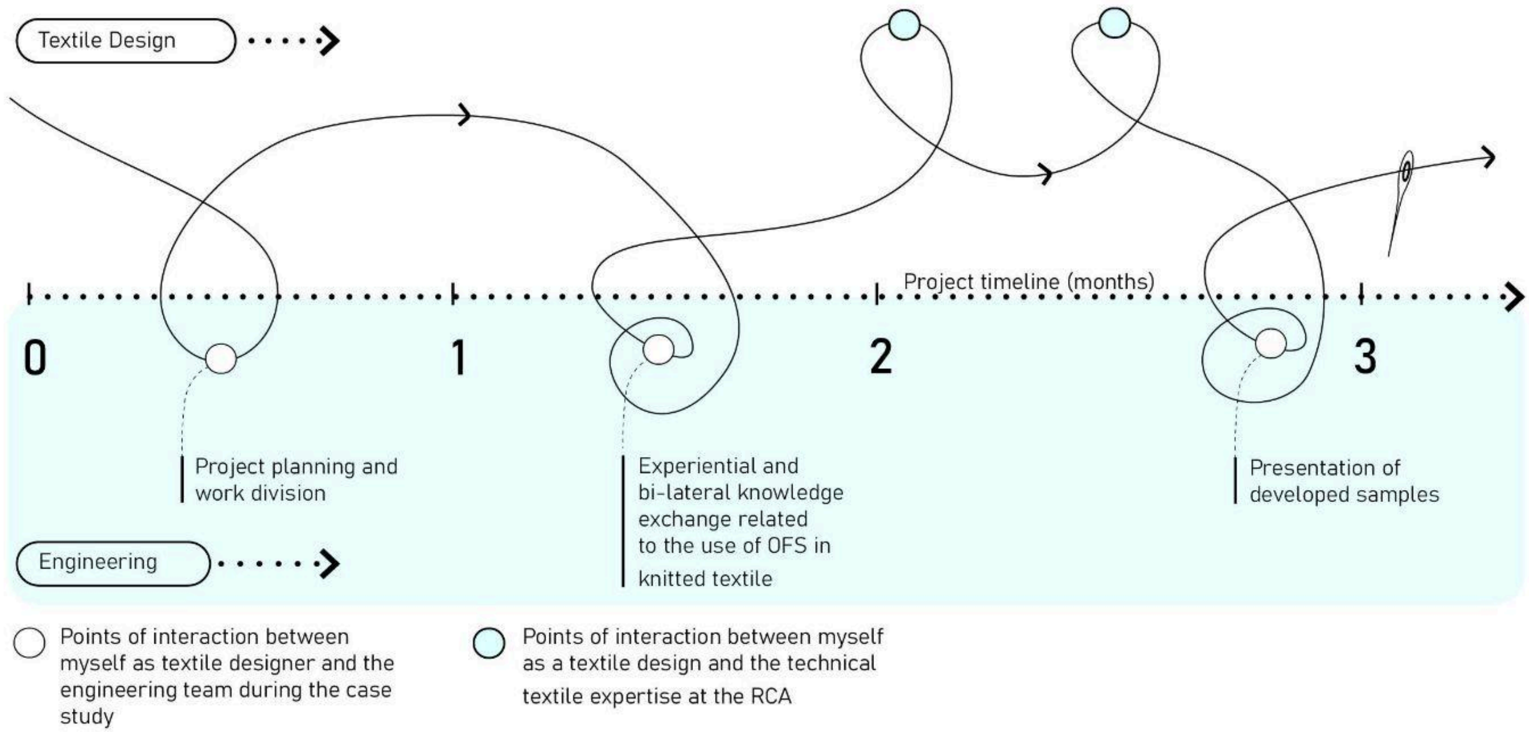


Figure 4.13. *The project's key points of textile design interaction. The central line divides the primary knowledge domains of engineering and textiles in addition to serving as a time axis.*

4.3.3.1. Implications and next steps

Working on multiple research strands within a new domain with previously unfamiliar materials was challenging and contributed to the sensory exploration becoming secondary to the functional and technical aspects of the project. Moreover, the project never progressed beyond the feasibility stage. Despite my uncertainties over whether the project would evolve into a more long-term undertaking, I approached it based on the assumption that it would. I had initially hoped that I would have the opportunity to spend more time on the development of the samples at a later stage, to iterate them further based on constructive and critical feedback from scientific project contributors, and to explore balancing their technical, functional and sensory considerations further.

My awareness of the ways in which the project was unable to promote the successful development of an interdisciplinary environment (as a result of too few physical and social interactions and insufficient involvement in developing the project brief) became a driving force in my approach to the design of the second research study, in which I endeavoured to establish a project that would allow me to become embedded within a smart textiles research environment and to work with scientific researchers with a higher level of daily interaction over a longer duration of time. While this case study ran for three months, the following case study ran for a six month period. Additionally, it was my intention to have greater input into the conceptualisation of the overall project.

This case study and the subsequent one share several similarities and differences. For instance, this case study focused on designing knitted textile samples for innersuits for operators working in high-temperature nuclear decommissioning environments, emphasising the integration of tactile and sensory considerations with technical functionality. While the following case study also involves knitted textile sampling, and was also concerned with the impacts of temperature on the wearer, yet focused on life supporting astronaut thermoregulation, my embedded role as a researcher provided me with a longer engagement period. This in turn has facilitated an opportunity to build on the foundational potential of the sampling undertaken in this case study, where, alongside sampling focused on tactile qualities and material integration, I have expanded my focus to include considerations related to application-specific wearability considerations. This was achieved through the design and development of a garment prototype. Further, through taking on different and varied roles in my position as designer, I was able to enhance my developing understanding of the role of the textile designer within this evolving field and to engage in smart textile environments to integrate and observe design insights. In addition, in this study, the adaptability required of the textile designer manifested as incremental responses to yarn properties and knitted textile structures, while in the following study, I was able to explore how it included creating a second project brief to align with the research goals. These are all explored in greater detail in the next chapter.

Chapter 5. Case study 2—Designing textiles for integrated networks of fluidic heating and cooling for astronauts' inner suits

5.1. The need for wearable thermoregulation in space

To build on the insights gained from the previous case study as regards how a textile designer can contribute to the design of wearable smart textiles and to address shortcomings of interdisciplinarity observed within it (see 4.3.3), I embarked on a six-month embedded residency within the Future AI and Robotics for Space (FAIR-SPACE) team at the Hamlyn Centre for Robotic Surgery (HCRS), Imperial College London (ICL). This immersion was strategic, allowing me to understand the FAIR-SPACE team's challenges from a first-hand perspective prior to exploring how textile design methods, practices and values might be able to contribute towards wearable thermoregulation in space. I also hoped to infuse more conceptual input into the design brief than was possible in the previous study.

Outer space is subject to extreme temperature fluctuations (from +121°C to –157°C). In the light of the potentially fatal impacts of changes of either + or –1.5°C to astronauts' core body temperatures[276], the need for optimally functioning thermoregulation garments in this environment emerges as a life-sustaining challenge. Although the first Apollo missions took place more than fifty years ago, the liquid cooling garment/liquid cooling and ventilation garment (LCG/LCVG) (see Figure 5.1a), which comprises the primary layers of the Extravehicular Mobility Unit (EMU) – a type of spacesuit (Figure 5.1b) – continues to be used today in contemporary space missions because of its efficiency[277] and has remained largely unchanged since the Apollo era.[278] A review of the literature highlighting the challenges and opportunities of LCVGs in space can be found in Appendix S.

[276] Xingxiang Zhang, 'Heat-Storage and Thermo-Regulated Textiles and Clothing', in *Smart Fibres, Fabrics and Clothing*, ed. by Xiaoming Tao (Elsevier, 2001), pp. 34–57, doi:10.1533/9781855737600.34; Panagiotis Kassanos and others, 'Towards a Flexible Wrist-Worn Thermotherapy and Thermoregulation Device', *Proceedings - 2019 IEEE 19th International Conference on Bioinformatics and Bioengineering, BIBE 2019*, 2019, pp. 644–48, doi:10.1109/BIBE.2019.00121.
[277] Amjed A.A. and Luma F. Ali, 'Liquid Cooling Garment Configuration and Investigation: A Classifying and Comparative Review', *International Communications in Heat and Mass Transfer*, 159 (2024), p. 108114, doi:10.1016/j.icheatmasstransfer.2024.108114.
[278] Kayla Marie Daniels, 'Thermal Performance Analysis of the Liquid Cooling and Ventilation Garment (LCVG) with Respect to Tubing Geometry', *ProQuest Dissertations and Theses* (University of North Dakota, 2019), p. 4 <https://www.proquest.com/dissertations-theses/thermal-performance-analysis-liquid-cooling/docview/2245841703/se-2?accountid=135034>.

Figure 5.1. *a) Front and back view of the LCVG worn on the male body. Image credit: NASA,* https://www.nasa.gov/audience/foreducators/spacesuits/home/clickable_suit_nf.html *b) The 21- layer A7L EMU space suit worn by astronaut Edwin. E. "Buzz" Aldrin as he walks on the surface of the moon on July 21 1969. Image credit: NASA,* https://www.nasa.gov/mission_pages/apollo/40th/images/apollo_image_12.html

5.2. Project objectives

The primary goal of the partnership between the RCA textile design department and the HCRS at ICL, within the scope of the FAIR-SPACE project, was to enhance the development of astronaut wearable technology systems being developed at the HCRS, ICL by embedding softness into 'prototypes' through textile methods. [279]

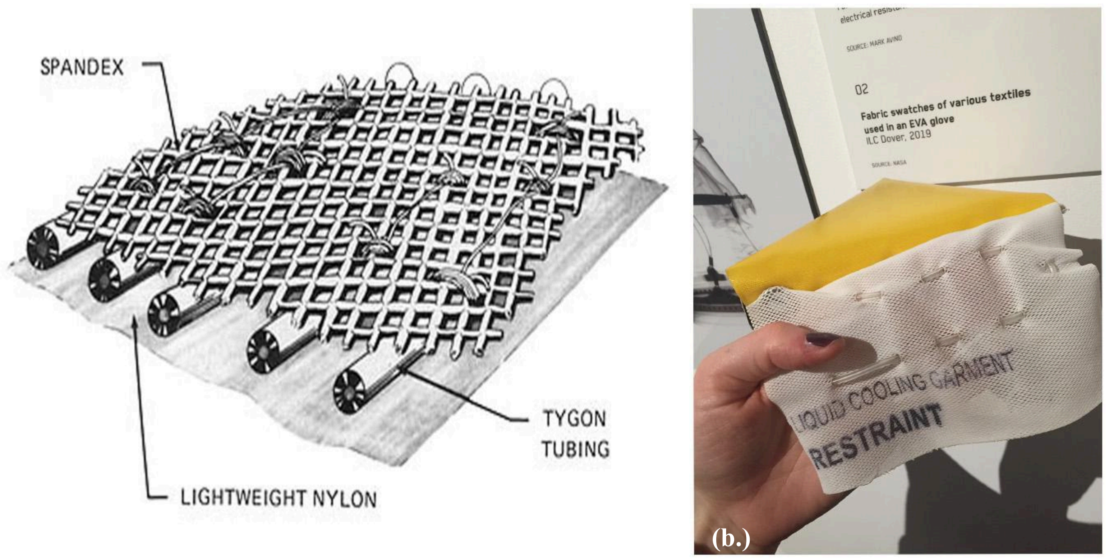
I was invited to bring my textile design expertise to bear on the ongoing challenge of producing wearable thermoregulation for use in space. The existing system (Figure 5.1) involves 91.5 metres (300 feet) of narrow tubing woven[280] somewhat crudely throughout a stretchy Spandex-knitted Lycra mesh (Figures 5.1a and 5.2). The LCG/LCVG's crucial function is the circulation of water through these tubes, which are laid close to the astronaut's skin (Figure 5.1a). The system relies on the flow of chilled water to remove excess heat while also drawing sweat away from the astronaut's body via vents in the garment's design.[281] My role focused on exploring the potential of textile design intervention and fostering opportunities for engagement with the technologies being developed by FAIR-SPACE researchers. Drawing on the technical and, crucially, the sensory and tactile expertise embedded within the discipline (essential for comfort and wearability), I addressed two main objectives:

1. To integrate the thermoregulatory features more seamlessly into the textile layers of the LCG/LCVG, creating a solution that is both functional and more sensorially pleasing, in terms of comfort and wearability.

[279] Further contextual background on the partnership between the RCA Textile Design Department and the HCRS, ICL is available in Appendix V.
[280] 'Solving Space - Cooling Garments - Space Center Houston' <https://spacecenter.org/solving-space-cooling-garments/> [accessed 10 October 2024].
[281] NASA, 'The Space Shuttle Extravehicular Mobility Unit (EMU)', *Suited for Spacewalking*, 1998, pp. 17–30.

2. To establish a production approach that is smooth and efficient, particularly in the light of an anticipated increase in demand for such thermoregulatory garments.

This demand arises from a growing need for more efficient life sustaining equipment as astronauts face more frequent and prolonged missions[282] on account of the construction of the International Space Station (ISS)[283] and forthcoming Mars missions.[284] The advent of commercial space travel,[285] with companies like SpaceX leading the way, and the transfer of these technologies to PPE and military applications[286] are also expected to contribute to this need. Thus, streamlined production methods could support a cost reduction likely to be pivotal in enabling their broader application.[287]



(a.) (b.)

Figure 5.2. *a) The tubing and fabric construction and material layers of the LCV/LCVG used in the Apollo missions. Image credit: NASA, (https://history.nasa.gov/SP-368/s6ch6.htm). b) LCV/LCVG tubing material construction. Image credit: Claire Felicity Miller (2020) taken at the London Design Museum's 'Moving to Mars' exhibition.*

My focus, to simultaneously enhance comfort, wearability and function, using straightforward production processes and drawing on textile design knowledge, was developed based on insights obtained during an initial review of the state of the art in astronaut thermoregulation (see Appendix F). However, the key

[282] Michael L Gernhardt and others, *Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems*, *Human Health and Performance Risks of Space Exploration Missions* (NASA, 2009), mmviii, 333–58.
[283] Victor. S. Koscheyev, Gloria Leon R., and Michael Dancisak J., *Liquid Cooling/Warming Garment. NASA Tech Briefs* (2010) <https://ntrs.nasa.gov/api/citations/20100009654/downloads/20100009654.pdf> [accessed 26 November 2023].
[284] V. S. Koscheyev and G. R. Leon, *Spacesuits: Development and Design for Thermal Comfort*, *Protective Clothing: Managing Thermal Stress* (Woodhead Publishing Limited, 2014), doi:10.1533/9781782420408.1.171.
[285] Barbara Brownie, *Spacewear: Weightlessness and the Final Frontier of Fashion* (Bloomsbury Publishing, 2020).
[286] Koscheyev, Leon, and Dancisak, *Liquid Cooling/Warming Garment. NASA Tech Briefs*.
[287] J.L.Leith and C.W.Hixon, *Development and Fabrication of an Advanced Liquid Cooling Garment*, 1976, pp. 1–9.

insights that revealed the emerging opportunity for textile design expertise within the traditionally ‘hard’ context of space exploration are as follows:

- Astronauts face more frequent and prolonged missions, requiring enhanced life-sustaining equipment, such as the LCVG/LCV, initially designed for shorter, less frequent missions, thus comfort becomes an increasingly important issue.[288]
- Despite the complexities inherent in the current designs,[289] thermoregulation garments may be enhanced through simplification and refinement of their ‘bulky and overly complex’ design.[290]
- The integration of psychological and sensorial comfort with thermo-physiological comfort[291] will be likely to benefit future space suit designs.[292]
- The fabric layer (Figure 5.2) of the LCVG/LCG has received comparatively little attention, as a means of enhancing thermoregulatory performance or wearer comfort, among researchers relative to other aspects, such as scaling down the size and weight of components, adjusting cooling liquid inlet temperatures and revising the tubing’s distribution layout and geometry.[293]
- With space travel expected to increase and be undertaken by both astronauts and commercial space travellers, as well as the possibility of broader terrestrial applications, the scale of production of LCV/LCVG is expected to increase, necessitating new production methods to support a reduction in current production costs.[294]

I developed two tailored textile design proposals that aimed to balance the project’s functional requirements with enhanced sensory and tactile attributes:

1. The development of a polymeric fibre with built-in heating functionality as the building block for a tunable heat-management smart textile system offering localised thermoregulation (Appendix L).
2. The design of wearable textiles with integrated fluidic heating and cooling networks for astronauts’ inner-suits (the focus of this case study).

The first proposal (Appendix L) aimed to build on work completed by the FAIR-SPACE researchers with whom I was engaging, who designed and demonstrated a ‘flexible’ wrist-worn thermoregulation device (see Figure 5.3a) by developing a softer, textile-based alternative.[295] This concept was informed by broader developments in smart textiles (see p.29), whereby functionality is increasingly integrated at the fibre level. The goal was to embed thermal management capabilities within a thermally drawn polymeric fibre that when embedded within a constructed textile would offer localised thermoregulation as a tunable

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[288] Gernhardt and others, *Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems*, mmviii.
[289] Janet Ferl and others, ‘Trade Study of an Exploration Cooling Garment’, 2008, pp. 2008-01–1994, doi:10.4271/2008-01-1994.
[290] Luis A. Trevino and others, ‘Flexible Fabrics with High Thermal Conductivity for Advanced Spacesuits’, 2006, pp. 2006-01–2236, doi:10.4271/2006-01-2236.
[291] Apurba Das and R. Alagirusamy, *Science in Clothing Comfort*, *Science in Clothing Comfort* (Woodhead Publishing India PVT Ltd, 2010), doi:10.1533/9780857092830.
[292] Ferl and others, ‘Trade Study of an Exploration Cooling Garment’.
[293] S.U.E Khan and others, ‘Physiological Adaptations in Space and Wearable Technology for Biosignal Monitoring’, in *Space Robotics and Autonomous Systems: Technologies, Advances and Applications*, ed. by Yang Gao (Institution of Engineering and Technology, 2021), pp. 275–340 (p. 45), doi:10.1049/PBCE131E_ch9.
[294] J.L.Leith and C.W.Hixon, *Development and Fabrication of an Advanced Liquid Cooling Garment*.
[295] Kassanos and others, ‘Towards a Flexible Wrist-Worn Thermotherapy and Thermoregulation Device’.

heat-management textile system aiming to replace the bulkier device with a softer, lighter and more flexible solution, thereby addressing issues of comfort and wearability highlighted in the literature.[296]

During the project, I worked with a medical robotics engineer specialising in MRI-guided endovascular interventions. Together, we worked on the early development of the thermally conductive polymeric fibre mentioned above. Unfortunately, owing to factors beyond my control and related to the funder's primary focus, this project did not progress past its initial stages and, with three months of the residency remaining, I redirected my research focus towards the second project, which centred on wearable fluidic thermoregulation systems. Although the initial project did not continue, it nonetheless served as the foundation for the engagement at HCRS, ICL and helped to shape the subsequent research. Moreover, it yielded valuable insights into the barriers that stood in the way of its advancement as well as highlighting the importance of a mindset capable of navigating such challenges and the feelings of disappointment that arose.

The focus of the revised proposal was on engineering a specialised textile that could house medical-grade fluidic tubing, with the aim of integrating these thermoregulatory components more seamlessly into the textile layers of the LCG/LCVG and then, at a later stage, connecting these to the FAIR-SPACE researchers' wrist-worn flexible device, thereby creating a solution that is functional, comfortable, and refined. I also considered textile methods that would be easy to produce, particularly in the light of an anticipated increase in demand for such thermoregulatory garments.

For this project, I engaged with an electronics engineer who specialised in medical device development. I designed and developed a series of embroidered/stitched (Appendix P) and engineered knitted textile samples (Appendix Q) that incorporated fluidic tubing and were intended to form a cohesively integrated network for wearable thermoregulation. These samples were intended as a progression from the 'flexible' wrist-worn device[297] that controls body temperature across the arms and torso. The combination of knitted samples, integrated fluidic tubing and connected device is intended to ensure astronauts' body temperatures are maintained within optimal ranges for comfort and functionality.

[296] Bruce Conger and Janice Makinen, 'High Performance Torso Cooling Garment', in *46th International Conference on Environmental Systems 10-14*, 2016, pp. 1–13.
[297] Kassanos and others, 'Towards a Flexible Wrist-Worn Thermotherapy and Thermoregulation Device'.

Figure 5.3. *a) Wrist worn thermoregulation device developed by researchers at HCRS, ICL. In: Panagiotis Kassanos and others, 'Towards a Flexible Wrist-Worn Thermotherapy and Thermoregulation Device',* Proceedings, 2019 IEEE 19th International Conference on Bioinformatics and Bioengineering, BIBE 2019 *(IEEE, 2019), pp. 644–48,* doi:10.1109/BIBE.2019.00121 *b) A HCRS, ICL researcher demonstrates his research to the RCA textile department team during one of the early show-and-tell meetings held at the RCA. c) RCA Researchers demonstrate a range of conductive fibres and printed electronics as part of the 'soft systems research' to the HCRS, ICL researchers.*

5.3. Design approach and sampling

I engaged with several technical considerations that are specifically related to wearable astronaut thermoregulation. I developed a multifaceted approach, initiating discussions with scientific researchers at HCRS, ICL and technical textile specialists at RCA & STOLL in the UK. This 'know-with' experience was complemented by a tour of the facilities and equipment at HCRS and participation in 'show-and-tell' sessions, designed to showcase capabilities on both the HCRS, ICL's side (Figure 5.3b) and the RCA's side (Figure 5.3c) of the engagement. It was during these sessions that I was able to observe the limitations of the technologies being developed at the HCRS, ICL, particularly in terms of the sensory and tactile awareness essential for wearability and comfort.

My multifaceted approach was supported by a review of the technical literature (Appendix S), 'know-what', which focused on the challenges and advantages of current wearable astronaut thermoregulation solutions (LCV/LCVGs.). The literature also offered insight into how motion interference can hamper device performance; this can be mitigated by improved garment comfort and fit. Such improvements might relate to the orientation of polymeric tubing in accordance with an astronaut's thermal profile to enhance cooling efficiency.[298] Alternatively, Iberall's lines of non-extension (Figure 5.4a) can be used to prevent motion-related buckling[299] (Figure 5.4b), thereby enhancing thermoregulation in those areas.[300] Finally, the literature review ensured that my selection of technical materials – specifically the types and dimensions of the polymeric tubing (Appendix M) – aligned with those

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[298] Conger and Makinen, 'High Performance Torso Cooling Garment'.
[299] Iberall Iberall, *Use of Lines of Nonextension To Provide Mobility in Full-Pressure Suits* (Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, 1969), pp. 1–44 <papers2://publication/uuid/9663B719-527B-4BE4-8B45-20179FCB2777>.
[300] Compton, 'Fit for Space: Leveraging a Novel Skin Contact Measurement Technique toward a More Efficient Liquid Cooled Garment'.

currently used in existing solutions. The aim was to apply this comprehensive understanding in tandem with my textile design 'know-how' to develop a textile design proposal that would meet the technical requirements effectively while offering contributions in the sensory and tactile realm. As mentioned, the initial proposal (Appendix L) did not progress beyond its initial stages, and the revised project proposal was thus designed to be less ambitious in terms of its reliance on technical project contributors and more realistic in terms of what could be feasibly achieved within the project's remaining time frame.

Figure 5.4. *a) Biomechanist Arthur Iberall's (1969) [CJ1] lines of non-extension for the upper part of the body. In: Arthur S. Iberall, Use of Lines of Nonextension to Provide Mobility in Full-Pressure Suits (Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, 1969), pp. 1–44 <papers2://publication/uuid/9663B719-527B-4BE4-8B45-20179FCB2777>. b) NASA LCVG gaping away from the body during motion as a result of a combination of stiff tubing and a finer fabric weight. In: Compton, 'Fit for Space'.*

5.3.1 The role of textile design expertise in technique and material selection

My key objectives cohered around the enhancement of existing solutions by focusing on integrating thermoregulatory features (i.e tubing) more seamlessly into the textile layers of the LCG/LCVG, creating a solution that is more comfortable, wearable and sensorially refined – which could also be easily produced using existing textile manufacturing processes and equipment. It was therefore necessary that I adopt an approach to textile sampling that focused on balancing the functional requirements of LCG/LCVGs with sensory awareness. My efforts to maintain this balance are evident in my decisions about which textile techniques and materials to use during the sampling process.

5.3.1.1. My approach towards selecting textile techniques

My selection of embroidery/stitch-based (Appendix P) and knitted textile techniques (see Appendix Q) was informed by my understanding of how these methods were well suited to produce textile samples, which could be comfortable, wearable and appealing from a sensory perspective, while also offering the desired functionality. This decision was also guided by my objective of finding techniques which demonstrated that they were easy to produce and second, by the literature, which suggested that a significant aspect of technical advancement in improving the thermoregulatory efficiency of LCV/LCVGs involves reorienting tubing layouts (i.e. aligned to an individual's temperature profile).[301] Consequently, my sampling aimed to preserve opportunities for prospective adjustments to the tubing orientation layout, designing with potential future changes in mind and keeping pathways of exploration open.

Initially attracted to embroidery and stitch-based techniques for their design flexibility and straightforward process, I explored a range of equipment and techniques that might be used to attach a range of medical-grade polymeric tubings to a knitted substrate (as outlined in Appendix P). However, challenges such as the substantial risk that the tubing would be punctured, coupled with the unpredictable behavior of the materials during machine embroidery – specifically, the tubing (platinum-cured silicone) flailing erratically as it entered the machine due to its elasticity and the stretch nature of the substrate – prompted me to re-evaluate my choice. Figure 5.5a highlights the impact of this unpredictable nature on the tubing's failing to remain securely attached to the fabric, which in turn contributed to its puncture. Despite attempts to mitigate this risk of puncture in the following samples, for instance, by altering the size of hole feeder on the cording device, adjusting stitch widths and the substrate, rotating the design in Sample 4 (Figure 5.5b), as well as moving towards manual machine techniques for better control (Figure 5.6), the need for constant vigilance against puncturing persisted.

[301] Conger and Makinen, 'High Performance Torso Cooling Garment'; Ferl and others, 'Trade Study of an Exploration Cooling Garment'.

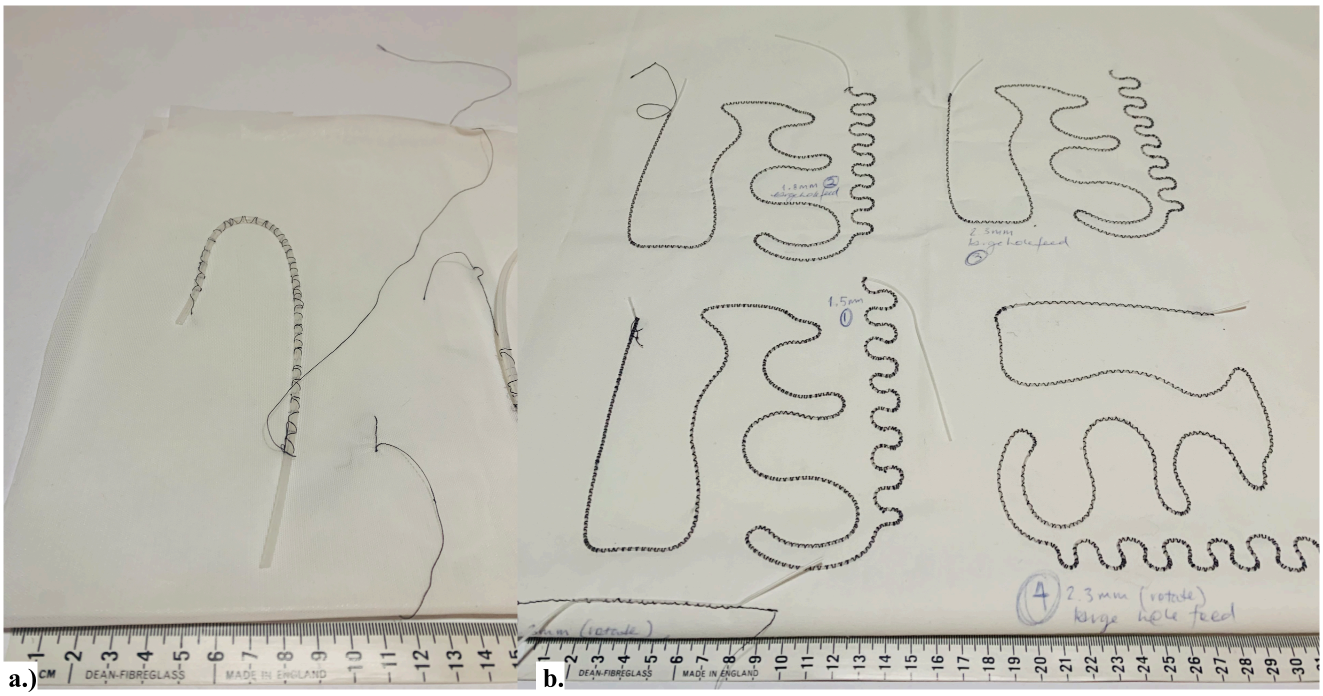

Figure 5.5. *a.) The tubing's (9) failure to remain securely attached to the substrate due to challenges associated with its integration and the stretch of the substrate during machine embroidery. b.) Attempts (Samples 2–4) to prevent tubing punctures during digital embroidery processes included altering the stitch width from 1.5 mm (Sample 1) to 1.8 mm (Sample 2) and 2.3 mm (Samples 2 and 3), changing the cording feeder between small and large hole-feed on the cording device, and rotating the design. The attempt visible here is the rotated design of Sample 4.*

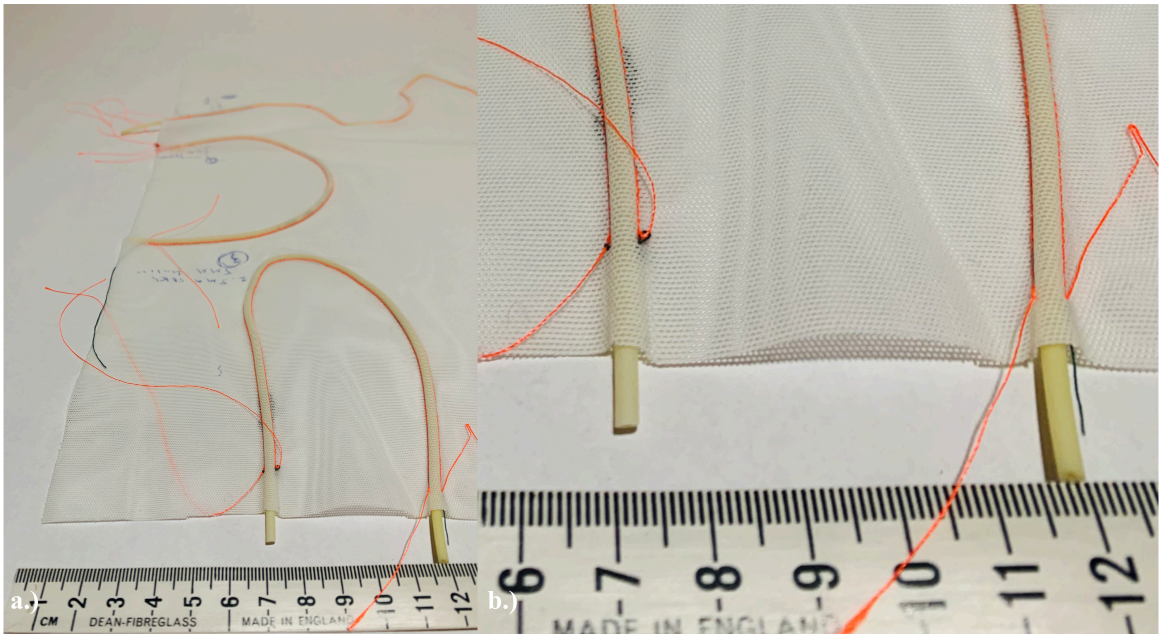

Figure 5.6. *Sample 11, produced on a domestic sewing machine (with a twin-needle embroidery foot) for greater control. The sample incorporates stretchy nylon/Lycra stretch mesh with integrated polymeric tubing where I sought to manually feed the tubing into the fabric to test the ease at which it would be possible to produce curved designs. a.) Curved design and b.) detail highlighting the bright colour chosen to visualise any puncturing.*

Even with these mitigations, including a finishing technique employed in fashion called 'coverstitch', which excited me aesthetically (Figures 5.7), meant that the risk of damaging the tubing remained a concern. Therefore, I shifted my focus onto knitted textile techniques that would allow me to insert the tubing post-knitting. This not only circumvented the puncture risks but also lent itself to a more seamless, integrated and comfortable design.

My exploratory process included attempts to create channels by which it would be possible to manually integrate the tubing using various knitting techniques, such as a French-braiding technique (Figure 5.8a-b). However, this did not afford sufficient exposure of the tubing to the skin, prompting me to proceed with industrial weft knitting(5.8c-e). This technique offered both the durability required for functionality and the potential for flexible design options. These included the ability to tune the sizes of the openings on the channels' skin side for effective skin contact and tubing pattern and distribution adjustments, both of which are fundamental to efficient thermoregulation. This selection also aligns with research that has indicated the potential of engineered knitted textiles for thermoregulation garments,[302] owing to their potential for:

- Customised and targeted performance that aligns with specific, anatomically mapped areas of the body, thanks to the adjustable placement of specific yarns – a strategy that NASA

[302] Özlem Kayacan and Arif Kurbak, 'Effect of Garment Design on Liquid Cooling Garments', *Textile Research Journal*, 80.14 (2010), pp. 1442–55, doi:10.1177/0040517509358800; Ferl and others, 'Trade Study of an Exploration Cooling Garment'.

researchers have described as beneficial for enhancing the efficiency of LCV/LCVG systems.[303]

- Scaled-up production, which has been made possible by advances in seamless and whole-garment knitting manufacturing processes.[304]

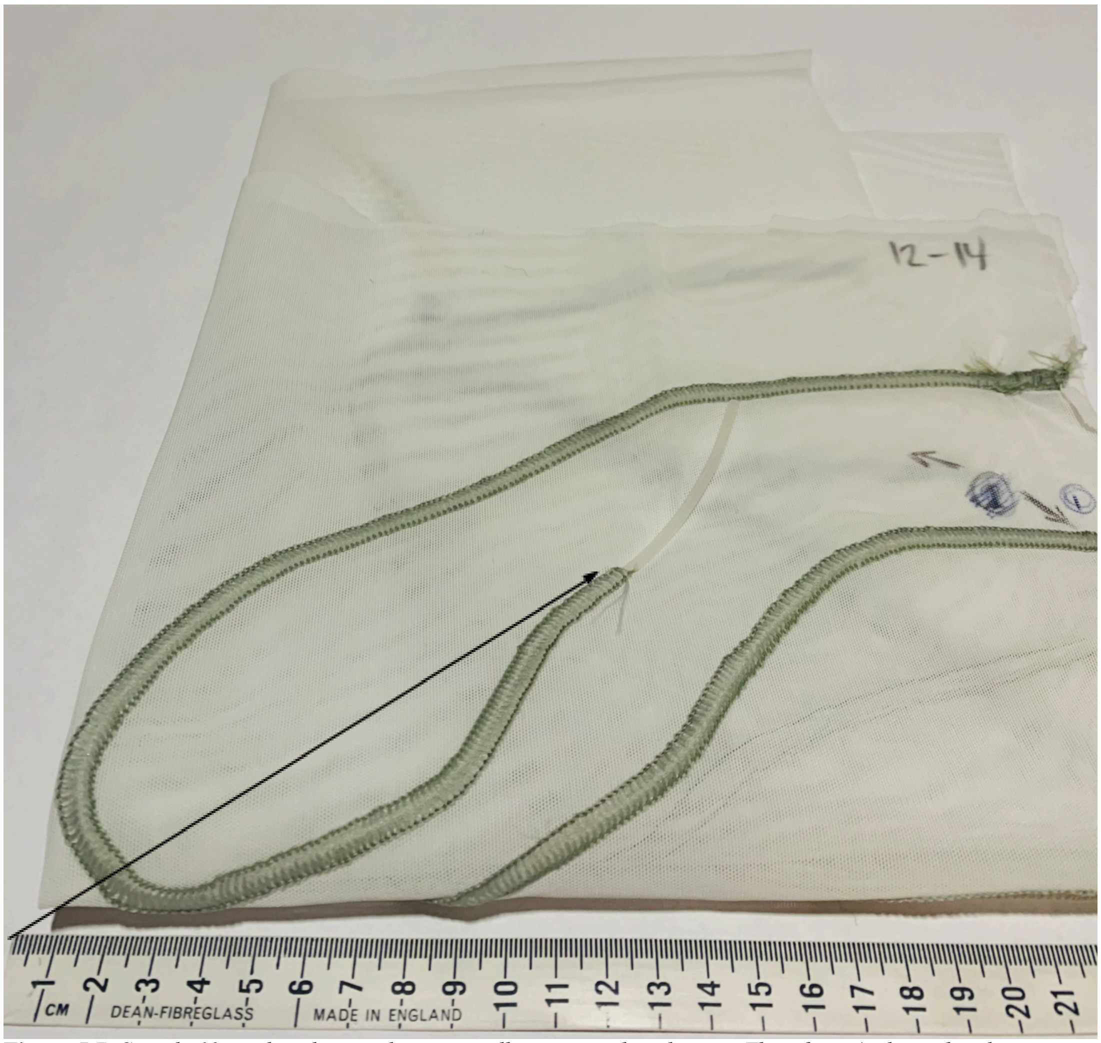

Figure 5.7. *Sample 12 produced using the two-needle coverstitch technique. The tubing (indicated with an arrow where it exits the fabric) has been stitched securely on the top side of the fabric, which is not possible when using the twin-needle embroidery foot on the domestic Bernina sewing machine.*

[303] Ferl and others, 'Trade Study of an Exploration Cooling Garment'.
[304] Subhankar Maity, Kunal Singha, and Pintu Pandit, 'Production of Seamless Knitted Apparels', in *Advanced Knitting Technology* (Elsevier, 2022), pp. 203–18, doi:10.1016/B978-0-323-85534-1.00012-X.

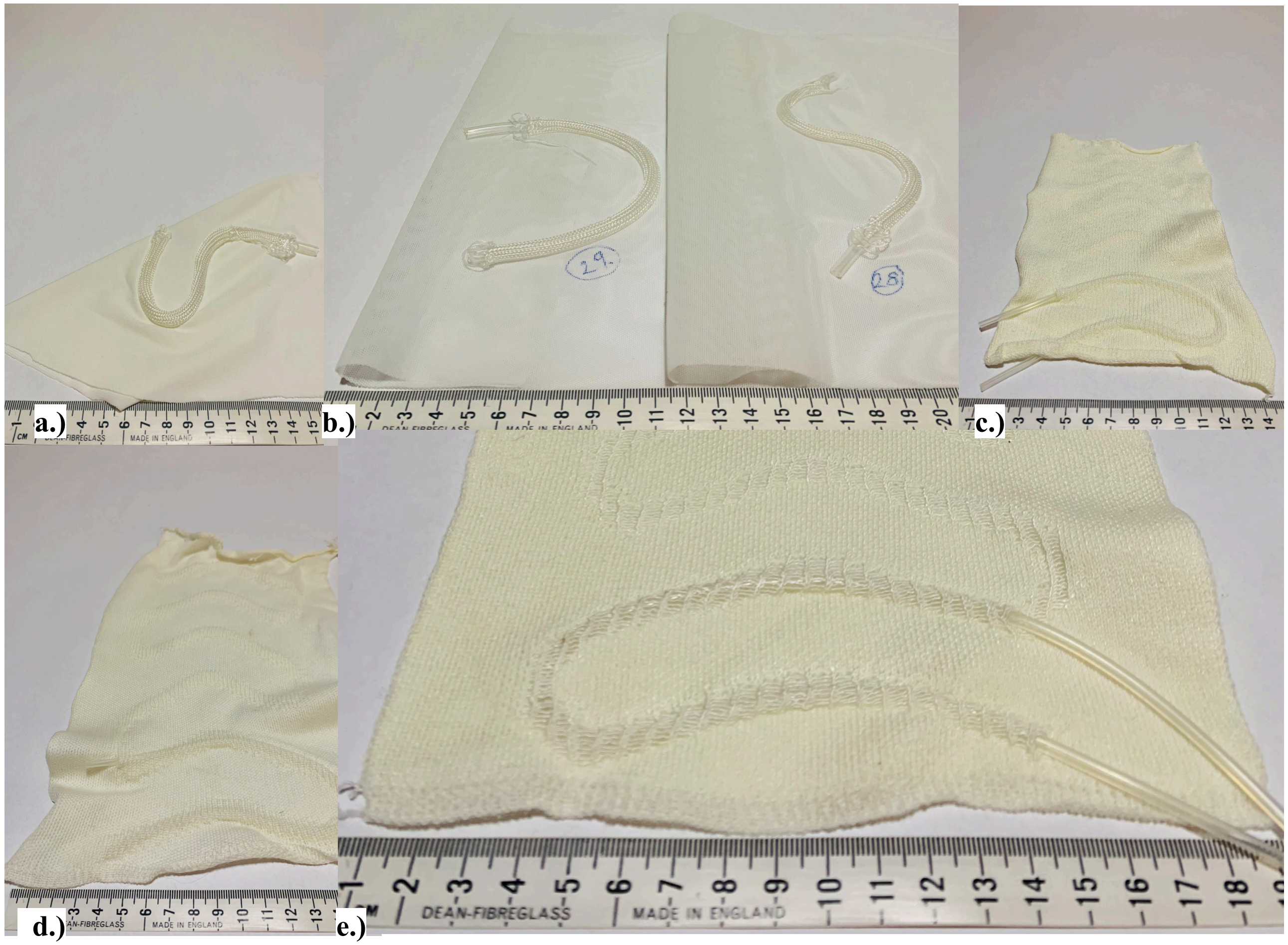

Figure 5.8. *French-braided knitted channels were created using a heat-fusible yarn through which the tubing has been fed. The package has then been fixed onto the stretch nylon/Lycra mesh. Sample a) 26. b) Samples 28 and 29. c) Face of sample 5 using yarn (c) in a single-jersey structure with integrated channels. This sample exhibits the most closed channels of all of those trialled, with every other needle knitting at the back of the channel. d) Back of sample. 5 e) A double-jersey, half-Milano, interlocking (on the face side) structured fabric, constructed using a combination of merino wool and a viscose, nylon and elastane-blend yarn. Every one in four of the stitches at the skin-facing side of the channels are knitted (Sample No.8).*

Drawing on my tacit, experiential and embodied knowledge (Sections 2.2.1.1. and 3.3.1) and honouring my disciplinary ownership of the textile design sampling process, I undertook the selection of techniques independently of the scientific researchers involved in the project. Although their expertise was expected to be invaluable for later testing phases, the engagement did not advance to those stages. Neither did I seek their input on the selection of textile materials because I did not consider these decisions to be a technically relevant or interdisciplinary concern at this stage (for more on this, see the next section). My most pressing concern was on exploring suitable techniques. Therefore, I operated with disciplinary independence and synthesising the information gained through the engagement, I proceeded in the hope that the scientific researcher involved in the project trusted me to make appropriate choices within my area of expertise. Through this process, I realised that full interdisciplinarity, in which all ideas are exchanged, is not invariably necessary. Instead, I recognised that independent exploration, informed by prior disciplinary input, enabled me to further develop and refine the design outcome.

A practical application of this approach was the independent creation of a garment prototype (Figure 5.9a; Appendix R) featuring seamlessly integrated channels (Figure 5.9b). This prototype was designed to connect to the wrist-worn thermoregulation device and aimed to demonstrate the research project's practical application and potential in a complete product. However, further scientific expertise was essential in one aspect: conducting an initial test to evaluate the fluidity of water through the garment's integrated tubing system. This test, illustrated in Figures 5.9c and further detailed in a video accessible via this link, used red ink to illuminate the flow.

Figure 5.9. *a) The image shows the prototype garment face-on. The tubing has been fed into the arm on the right. b) Detail of the prototype garment, with an arrow indicating the seamlessly integrated knitted channels. c) An evaluation of the fluidity of water through the garment's integrated tubing system using red dye. Garment reversed to visualise the evaluation. d) Detail of the face-side of the garment during the evaluation.*

5.3.1.2. Selection of materials

My selection of materials (see Appendix N) was also guided by my aim to strike a balance between technical requirements and sensory/aesthetic considerations. My choice of materials (Table 5.1) was guided by my practitioner experiential knowledge to tactilely assess their suitability for comfortable and wearable textiles using touch. This involved a sensory and tactile examination of various aspects, such as the materials' softness to the touch, their drape and their adaptability to my chosen techniques, which included embroidery, stitching, and knitting. I also considered their availability during the sampling phase. While visual aesthetics were considered, they were tethered to the constraints of functional parameters.

Table 5.1. Materials selection rationale

Material Component	Material type	Role	Rationale
Threads	Cotton	To fix the tubing to a substrate in the embroidery and stitch-based samples.	- Compatibility with the machines used; - Readily available within the textile workshops; - Common use within fashion and textile-production processes.
	Polyester		
Substrates	Nylon/Lycra stretch warp-knitted mesh	The main substrate for the embroidered and stitch-based samples	- Demonstrative purposes; - Its stretchy and breathable nature; - Similarity to that which is used in the current LCG/LCVG; - Colour.
Yarns	A cream viscose, nylon and elastane blend.	To enhance softness, drape, stretch and recovery	- Soft handle; - When steamed provides excellent stretch and recovery, essential for snug fit of both integrated tubing and body when worn.
	Merino Wool	The yarn for the main body of the sample.	- Thermoregulatory, antimicrobial and hypoallergenic properties; - Lower sustainability impact of natural vs. synthetic materials; - Compatibility with the machines used; - Colour; - Soft, tactile qualities, for increased comfort.
Tubing	**-Surgical-grade medical tubing** -Platinum-cured silicone, thermoplastic elastomer (TPE); -Biopharmaceuticals tubing (BPT); - Polyvinyl chloride (PVC); - Polytetrafluoroethylene (PTFE).	An integrated fluidic network, which is intended to start and end at the wrist where the wrist-worn device sits, is housed within the polymeric tubing	- Ensure materials used within sampling process align with the materials listed in the state of the art (matching the dimensions and/or the polymer of the tubing used in the current LCG/LCVG); - Readily available in the HCRL, ICL, to act as a placeholder during the sampling process.

This is exemplified by my selection of high-contrast yarns, specifically those in neon colours, to highlight stitch paths and tubing punctures (see Figures 5.10a and 5.10b). This selection not only aligned with my natural inclination to infuse my work with sensory/aesthetic value but also lent a vibrant ‘sporty’ appearance to the samples, embodying a kind of practical, or ‘reductionist aesthetics.’[305] However, I found it increasingly challenging to navigate the interplay between the technical objectives, the unfamiliarity of the materials and the scientific environment. To better manage the sense that the technical and aesthetic objectives were competing for my attention, and to effectively manage the tension and feeling of overwhelmed that I experienced at encountering a domain that required me to adapt to new ways of thinking, I made a conscious decision to restrain myself from further exploring visual aesthetic curiosities emerging from the colour interactions. Given that such visual aesthetic awareness was something that I was confident I could easily contribute, I could first maintain a sharp focus on the technical aspects without incorporating additional aesthetic ‘distractions.’ One of the ways I did this was by selecting a colour palette that was largely restricted to creams and whites for the substrate and knitted textile samples, which also enabled me to harmonise my developments with the colour of the LCG/LCVGs (Figure 5.10). In addition, I prioritised the creation of something for initial interdisciplinary discussion during the early stages of the sampling process.

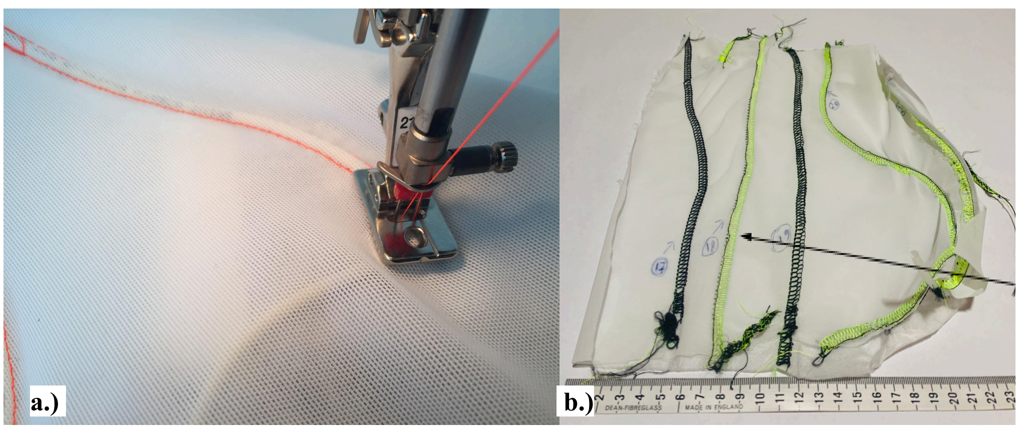

Figure 5.10. *a) Detail of sample 9 showing the high-contrast neon orange yarn securing the polymeric tubing on the underside of a white nylon/Lycra stretch warp-knitted mesh using a twin-headed needle. b) Arrow indicates Sample 18 exploring the use of the cover-stitch to integrate the polymeric tubing into the white nylon/Lycra stretch mesh using a neon yellow, lime green and black-threaded colour combination.*

[305] Sarah Elizabeth Braddock Clarke notes that ‘by streamlining elements in smart clothing redefinitions of modernism are presented, where the simple, clean, pure, clear and efficient offer reductionist aesthetics’: Clarke, ‘Clothing + Embedded Technology’, p. 9.

5.3.1.3. Tubing selection and specialist input

My selection of the flexible polymeric tubing (Appendix M) exemplifies the shift from individual decision-making to a process shaped by external expertise. My initial selection was primarily based on understanding the materials used in the current LCG/LCVG. However, input from the scientific researcher who I was working with was invaluable, addressing concerns beyond my knowledge domain, such as the impact of tubing size on pump functionality, and using their expertise to verify the tubing's properties for the intended use while also taking charge of the order once the decisions had been made.

This approach to material selection marks one of the ways in which the engagement required me to alter my traditional methods. The reliance on material data sheets (MDS) for selection contrasted starkly with the hands-on approach to which I was accustomed. Such methods of acquiring materials are representative of the industries in which they are ordinarily used, in which the materials' sensorial nature is not relevant. For instance, much of the sampling described here uses tubing acquired from Cole-Parmer. This company provides medical and surgical grade tubing to various industries, including pharmaceuticals and fluid handling. Material selection in textile design is typically a tactile and visual experience, often involving physical samples/swatches or in-person visits to a tradeshow, store or material library.

5.3.1.4. Integrating polymeric tubing into textiles

To begin materialising the potential for my hands-on engagement, I was obliged to bridge the interdisciplinary gap by integrating the polymeric tubing into the textiles. Several specific challenges arose, as follows:

- 'Translating' the material measurements: one obstacle was the adaptation of the flexible polymeric tubing dimensions to suit the specifications of the digital embroidery machinery. Specifically, I was obliged to translate the standard measurements of the tubing (wall, internal and external diameters) used in typical applications into millimetres. This was crucial to ensure that the stitch measurement was sufficiently wide and high to avoid puncturing the tubing during stitching. To accomplish this, I had to consult a scientific project contributor to understand the conversion calculations before re-engaging with embroidery experts at the RCA.
- Tubing length constraints: the flexible polymeric tubing was available in 15-metre lengths, which was insufficient for the digital embroidery machine. I overcame this by tying two lengths of tubing together to meet the length requirement.
- Winding the tubing onto a spool: another hands-on task that involved manually winding the tubing onto a spool, making it compatible with the digital embroidery machinery.

These activities highlight the simple and unexpected yet vital steps that can impede engagement across disciplinary boundaries. My metaphoric identity as a 'material explorer' supported in reducing the inherent pressures of addressing unforeseen issues, such as converting measurements. By viewing these more technical moments as integral to the exploration process, I was able to see them as necessary steps toward bridging the gap between ‘soft’ textile methods and scientific approaches in smart textiles design. In addition, the conversion of measurements served as a gateway to understanding the tacit material knowledge of scientific contributors involved in the project, prompting me to reflect on instances of my own tacit expertise, such as threading a sewing machine or selecting the appropriate thread for stitching. Despite working with textile machinery and equipment, I found that several manual interventions were necessary for sampling, underscoring that material innovation is not solely a product of advanced technology. This aligns with the observation of Louise Valentine and others[306] that current interdisciplinary endeavours in art, science and design are inducing a shift in both functionality and the manufacturing process. Given that this intersection of textile technologies is in its early stages, such innovative textiles are yet to be produced on a large scale and still require handcrafting.

During the process, I observed that the different polymers used for the flexible tubing exhibited distinct surface qualities. For instance, the tacky surface of the platinum-cured silicone made it challenging to pull it through a knitted channel or stitch into a fabric without it getting caught against the machine. Conversely, PVC tubing, with its smoother surface, moved effortlessly across the fabrics.

5.3.1.5. Tubing layout

When designing the tubing patterns, I was influenced by a scientific project contributor who suggested serpentine patterns could maximise space (thereby offering greater tubing coverage and therefore, more efficient cooling) and that such patterns can effectively regulate water flow and pressure. I also referred to existing patterns in the literature[307] (Figure 5.21a–e) and examples seen in person at the Design Museum’s *Moving to Mars* exhibition (Figure 5.21f). These examples highlight significant variability in tubing patterns and distribution reflecting an observation in the literature that there is a notable lack of detailed engineered designs for optimal patterns, distributions, and geometries, and that patterns often prioritise manual ease or rely on ‘randomness.’[308] Based on this, I designed patterns that incorporated a range of curvatures to ensure that future flexibility was ‘designed-in.’ For instance, Figure 5.12 illustrates samples 2– 4, which feature embroidered curves of varying sizes.

[306] Valentine and others, ‘Design Thinking for Textiles: Let’s Make It Meaningful’, p. 966.
[307] Amjed A.A. and Ali, ‘Liquid Cooling Garment Configuration and Investigation’, p. 6.
[308] Amjed A.A. and Ali, ‘Liquid Cooling Garment Configuration and Investigation’.

(a.) (b.) (c.)

(d.) (e.) (f.)

Figure 5.11. *a) Wavy vertical serpentine pattern. In: Mammadbaghir Baghirzade and others, 'Experimental Evaluation of Microclimate Cooling Garments Under Controlled Ambient Conditions', in ASME 2019 International Mechanical Engineering Congress & Exposition, 11-14 November 2020, Salt Lake City, Utah (American Society of Mechanical Engineers Digital Collection, 2020), doi:10.1115/IMECE2019-10679, p.3. b) Vertical serpentine pattern. In: Grazyna Bartkowiak and others, 'Influence of Undergarment Structure on the Parameters of the Microclimate under Hermetic Protective Clothing', Fibres and Textiles in Eastern Europe, 81.4 (2010), pp. 82–86. c) Organic wavy serpentine pattern. In: Joseph M. Jessup,'Hybrid Enhanced Epidermal Spacesuit Design Approaches', (unpublished doctoral thesis, University of North Dakota, 2015), p.41 d) Organic wavy serpentine pattern. In: Soumyajit Sarkar and V. K. Kothari, 'Cooling Garments—A Review', Indian Journal of Fibre & Textile Research (IJFTR), 39.4 (2014), pp. 450–58, doi:10.56042/ijftr.v39i4.7734. p.452. e) Horizontal serpentine pattern. In: Jingxian Xu and others, 'Novel Design of a Personal Liquid Cooling Vest for Improving the Thermal Comfort of Pilots Working in Hot Environments', Indoor Air, 2023.1 (2023), p. 6666182 (p. 4), doi:10.1155/2023/6666182. p.4. f) Red loose wavy serpentine pattern. Liquid cooled high-altitude garment. Image credit: Claire Felicity Miller (2020) taken at the London Design Museum's 'Moving to Mars' exhibition.*

5.4. Analysis and opportunities for future research

Beyond addressing the technical objectives (5.2), this case study has enabled me to explore how textile design methods, practices and values might contribute towards wearable thermoregulation in space. My analysis has drawn on reflection-*on* action throughout the making process supported by active documentation methods such as photography, sketches and diagrams.[309] Additionally, I incorporate my personal experiences of interdisciplinary engagement during their production.[310] The approaches I adopted to develop the knowledge and understanding required to produce in this context are also considered part of the making process. I also considered the role of the textile designer in light of the value and contribution of the discipline's methods and practices. The insights gained from this interpretive, reflective analysis are intended to contribute to the future design and development of wearable smart textiles. These insights support an understanding of how the textile designer who draws on their experiential and exploratory textile knowledge can contribute. In the following sections, the analysis is looked at in relation to an approach to practice, interdisciplinarity and finally opportunities for future research.

5.4.1. Approach to practice

The research and practice presented here has required adaptability and flexibility on my part, due to the distinct, dynamic and evolving needs of the case study (i.e. when the initial project proposal (Appendix L) stalled, I was obliged to revise my approach). This led to a second proposal – the focus of this study – in which I proposed the development of embroidered (Appendix P) and knitted textile samples (Appendix Q) that incorporated networks of flexible tubing designed for wearable astronaut thermoregulation. These were designed to facilitate heating and cooling when co-integrated with a flexible wrist-worn device developed by scientific researchers at HCRS, ICL. Their significance lies not only in the analysis of the application of my textile design expertise to this domain; they also serve as reflective tools, offering a unique vantage point from which to examine my experiences and engagement within the team at HCRS, ICL.

For instance, while revising the project brief, I had to navigate the disappointment that surfaced and let go of my attachment to the previous idea, which could not be realised due to resource or technical limitations. I had to accept the situation, as it was due to constraints beyond my control that affected and impeded the project's progression. I began now to recognise the characteristics of the approach required to contribute effectively within such an environment. This introspection is crucial for a deeper understanding of how the combined practical and intellectual approaches to textile design can contribute to the design of wearable smart textiles.

5.4.1.1. Navigating roles and learning modes

This case study has operated within the realms of qualitative and exploratory research. I have exercised a soft textile approach to Frayling's[311] RtD by assuming the following key roles: desk-based researcher, embedded researcher and maker.

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[309] Schön, *The Reflective Practitioner*; de Freitas, 'Towards a Definition of Studio Documentation: Working Tool and Transparent Record'.
[310] Clandinin and Connelly, 'Personal Experience Methods'.
[311] Frayling, 'Research in Art and Design'.

As with case study 1, I was obliged to move flexibly between roles and learning modes during the research and practice. Once again, I employed the 'know-what', 'know-how' and 'know-with' learning modes. Their combination has offered me a comprehensive approach to developing material and contextual knowledge and understanding crucial to my participation as textile designer. However, these understandings have manifested differently in this study on account of the project's different context, scope and interdisciplinary engagement.

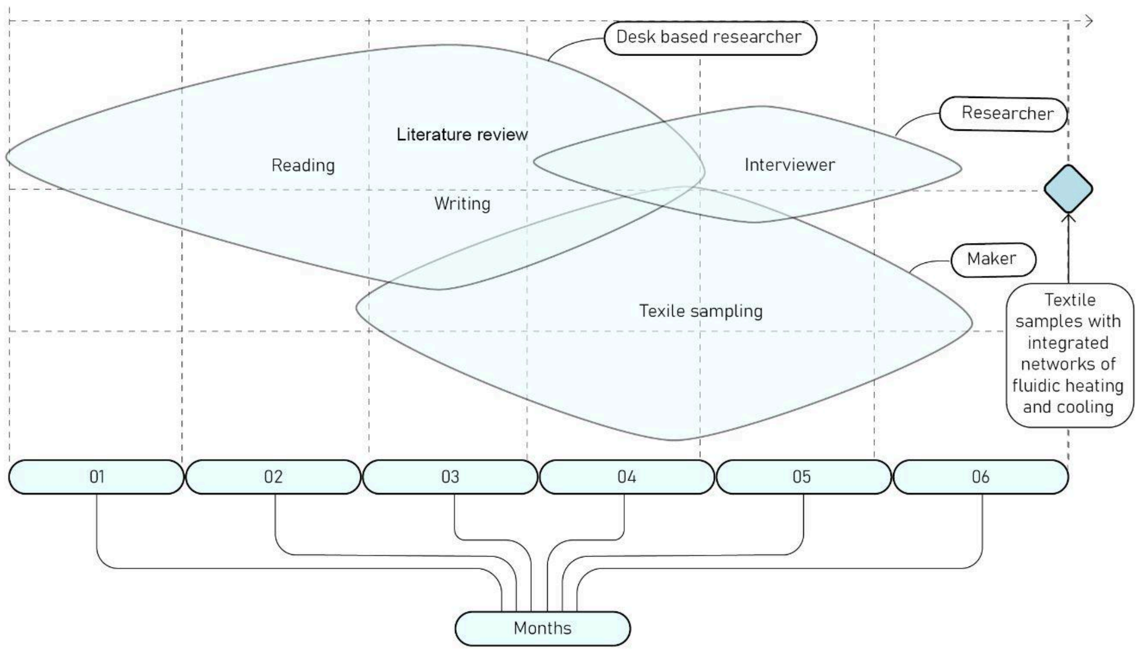

Figure 5.12. *The key roles and their associated methods and activities undertaken during the textile design research process.*

Following the approach adopted in the previous study, I assumed the role of desk-based researcher engaging with the practical and technological challenges encountered by scientific researchers at HCRS, ICL. I relied on the 'know-what' learning mode and conducted a literature review. Here, it was necessary I do this twice owing to shifts in the research focus. Therefore, a significant amount of time was spent in 'know-what' learning mode as I worked to identify an intervention point (see Appendix L where the relevant literature is contained within the project brief; and Appendix S for literature relevant to the project presented in this case study). This enabled me to:

- Expand my understanding of the state of the art in terms of wearable thermoregulation.
- Identify areas in which I could contribute.

Some of this literature was recommended by the scientific project contributor, whom I was working with, and relevant to our area of research, offering a point of connection and support for our developing relationship. However, despite my openness and willingness to engage with their literature, I did not feel as though this was reciprocated. This led to further feelings of disappointment, probably due to my recognition that the scientific project contributor I was working with was unable to commit fully to interdisciplinarity as a result of existing commitments (it is also possible that they were simply unwilling). This demonstrates how the scientific project contributor was unable to offer me the level of engagement or feedback that I had hoped for. The process of searching for technical literature in the library not only gave me access to material that I would not otherwise have accessed, supporting my growing familiarity with ICL's distinct scientific research atmosphere; it contrasted with RCA's art and design library in terms of size, the kinds of users it attracts and the materials housed within it.

In addressing my project objective, I recognised the importance of fostering stronger interdisciplinary interactions across sectors and fields. Thus, I expanded the 'know-how' learning mode to include a broader familiarity with a culture or specific work approach. I did this through my role as an embedded researcher, which included enhancing my familiarity with the research culture at ICL by participating in 'show-and-tell' meetings between RCA and ICL. At these meetings, HCRS researchers exhibited their work (Figure 5.3b), while RCA's Textile Design department presented their smart textiles research (Figure 5.3c). I also engaged in feedback meetings with the scientific project contributor I was working with, during which I shared my progress in sampling. Although these examples did support me in familiarising myself with and enriching my grasp of smart textile design and its associated research challenges (and the environments out of which such challenges are born), they may not have gone far enough, and could have been built on further to enhance the experience and outputs of the research, perhaps through a workshop format. These roles and the key methods used, their activities, outcomes and the learning modes with which they are associated are summarised in Appendix T.

I also adapted the 'know-with' learning mode from interdisciplinary making to the semi-structured interview; this offered a different approach to engaging researchers and practitioners across the broader engagement. Through this, I further developed my understanding of how a textile designer can engage and participate within scientific settings focused on smart textiles.

Finally, another important aspect of navigating these roles and learning modes has been the physical, embodied nature of the process. Both in terms of my role as maker – engaging physically with new and unfamiliar materials – and my physical position as 'embedded researcher' at the HCRS, ICL while maintaining access to key RCA textile facilities. This movement was not merely physical, but was also metaphorical, bridging the gap between distinct realms of thought and practice. Drawing on Sennett's notion of the body as the means through which we engage and experience the world,[312] my physical presence and intentional movement between the institutions served as a vital connector that allowed me to address my research objectives. Lean's[313] description of her physical presence as an 'outsider' in industry at an intelligent textiles company, acting as a probe, in itself resonated with my experience, emphasising that work of this nature is made possible and facilitated by those who are willing to 'connect the dots'.

[312] Sennett, *The Craftsman*, p. 50.
[313] Lean, 'Materialising Data Experience Through Textile Thinking', p. 98.

5.4.2. The role of interdisciplinarity

This study aimed to address factors that had limited the previous case study from achieving interdisciplinarity (4.3.4.1.). I lengthened the duration of my engagement and embedded myself within the scientific research setting of the HCRS, ICL. I hoped that this would facilitate a more direct experience in the smart textiles research environment, thereby enriching my understanding of the potential of ‘soft’, textile design approaches in such contexts. Central to this approach was my ambition to influence the conceptualisation of work at its initial stages by means of textile design thinking. This aim aligned with Toomey and Kapsali’s[314] D:STEM concept, in which they advocate for early engagement with textile design skills to enable significant shifts in innovation.

As previously mentioned I was invited to contribute to ongoing work at the HCRS, ICL without specific expectations from scientific project contributors. Initially, I proposed a textile design-led concept aimed at creating a ‘softer’ alternative to the ‘flexible’ wrist-worn device (see Appendix L). However, this first proposal struggled to progress owing to heavy reliance on scientific project contributors’ fabrication facilities, expertise and methodologies.

Consequently, I altered the project goals and brief to be less reliant on scientific project contributors. However, proposing design alternatives using textile methods is challenging; one must first get to grips with an overwhelming quantity of technical information presented in unfamiliar formats, such as scientific research papers. This time-consuming process is energy-intensive. In my case, it had to be undertaken twice, which detracted from the time available to be spent on hands-on experimentation. As a result, the textile outcome, initially envisioned as a smart textile, became merely functional, supporting an existing device rather than offering a new design concept. Despite my initial well-meaning intentions to work in a way that would have required interdisciplinarity, the existing practical demands on my collaborators' the scientific researchers at HCRS, ICL ultimately prevented this.

Figure 5.23 illustrates the duration of my journey at the HCRS, ICL, tracing my movement between the fields of textile design and engineering. The diagram illustrates how, although most of the time was spent within the field of engineering, the proposal developments and production process took place in the textile design domain (to which I returned after reviewing the literature and receiving critical feedback from scientific project contributors). It also highlights that my second proposal was developed over half way through my embedded residency, following the stalling of the first. Although the project initially appeared to offer the potential for interdisciplinarity, it gradually evolved into a multidisciplinary project structure, as defined by Klein.[315] In this structure, textile design sampling was performed using discipline-specific methods and informed by engineering. The device and the knitted textiles have been developed within domains of disciplinary independence, bound not by shared methods or tools integral to

[314] Anne Toomey and Veronika Kapsali, ‘D-STEM: A Design Led Approach to STEM Innovation: 5th STS Italia Conference: Making Society through Science and Technology’, in *A Matter of Design: Making Society through Science and Technology Proceedings of the 5th STS Italia Conference*, ed. by Claudio Coletta and others (STS Italia Publishing, 2014), pp. 425–38 (p. 11).
[315] Thompson Klein, ‘A Taxonomy of Interdisciplinarity’, p. 17.

their production, but rather by the potential of their coming together, which, as previously mentioned, was not fully realised.

Pfirman and Martin[316] observe that interdisciplinary projects often begin positively before encountering difficulties, particularly when the researcher is reliant on others' strengths and skills. This corroborates my experience where I observed for the same reasons that interdisciplinarity can extend the scope and potentials of textile design practices beyond the familiar and into hitherto unfamiliar domains, it can also impede the progress of projects that rely too heavily on the input of others.

[316] Stephanie Pfirman and Paula J. S. Martin, 'Facilitating Interdisciplinary Scholars', in *The Oxford Handbook of Interdisciplinarity*, ed. by Robert Frodeman, Second Edition (Oxford University Press, 2017), pp. 586–600, doi:10.1093/oxfordhb/9780198733522.013.47.

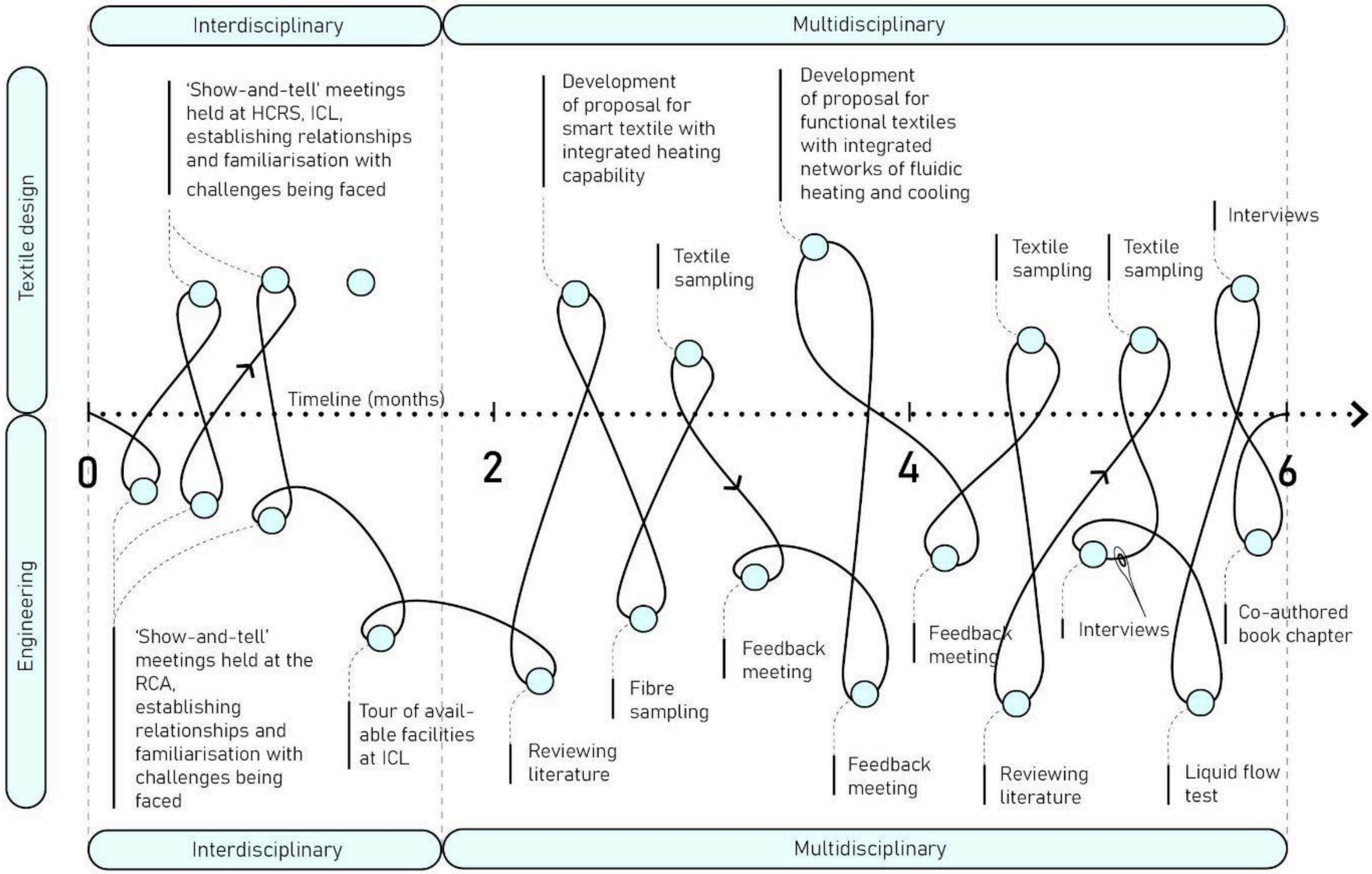

Figure 5.13 *The above diagram charts my journey (illustrated by a line) throughout the project during the six-month engagement period. Key points of interaction within the two projects, their chronology and positioning within either the field of textile design or engineering are highlighted. The point at which the project shifted from interdisciplinarity to multidisciplinarity is also indicated.*

5.4.2.1. The challenges and opportunities of working and making between different knowledge domains

Although working across knowledge domains as a textile designer offers considerable opportunities, when multiple actors influence the progression of a project, inevitable challenges and setbacks are also likely to arise, as this case study has revealed.

The difficulties that I encountered in my attempts to effectively balance my sensory and tactile design concerns with the projects' technical demands are exemplified by the challenge of communicating the value of my contribution to the project in terms of sensory enhancement. This challenge manifested during the aforementioned show-and-tell and feedback meetings, when I recognised that the scientific contributors that I was working alongside considered technical elements to be of higher value in the sampling process. A secondary challenge related to my attempts to meet the technical requirements, which caused the sensory considerations to become largely secondary. This led to the sense that neither aspect was fully realised in my work.

For instance, the dominant technical concern of tubing puncture constrained my ability to further explore the use of colour in the sampling process, and I parked or 'reined in' any further consideration of this aspect. In an attempt to adequately address the technical aspects of the sampling process, it was these aesthetic curiosities and its potential, which I imagined as the starting point for future exploration, that sustained and fed my curiosity during the sampling process. However, despite prioritising the technical elements, they too reached a point at which further progress was not possible without additional input from scientific researchers.

At the heart of this sensory/aesthetic challenge lies the challenge of engaging across disciplines. Although the scientific project contributor I worked with invited me to ask questions at any time, in reality, this was not always possible or appropriate. While this was an important project for me, it was one of many existing research commitments for them and I witnessed the prevalent 'publish or perish' culture in scientific research, which offers little flexibility for interdisciplinary exploration without overburdening researchers or increasing their workload. This aligns with Klein's observations that some of the barriers and disincentives to interdisciplinarity in academic research settings include a reliance on 'volunteerism' and 'overload.' She further notes that university cultures can impose barriers to work progression.[317] This aligned with my experiences as I perceived the environment to be a closed one, which diminished my ability to ask questions and challenged my confidence. The project exposed a disparity between my expectations of working across disciplines and the reality, when I encountered a solemn office space in which researchers worked in a silent and focused manner at their desks. I felt more comfortable working in the RCA textile studios, surrounded by piles of fabric and background noise, and my time at ICL was predominantly spent engaged in reviewing literature. I have speculated as to whether factors such as gender, age and academic status have played a role in my ability to engage in the manner I had hoped or

[317] Julie Thompson Klein, *Creating Interdisciplinary Campus Cultures: A Model for Strength and Sustainability*, The Jossey-Bass Higher and Adult Education Series, 1st ed (Jossey-Bass/Association of American Colleges and Universities, 2010), pp. 72–73.

envisioned or, more specifically, in a manner that was more conducive to the further development of interdisciplinary outcomes. It has also been observed that some counter-productive dynamics – for instance, around status and value – can be amplified in interdisciplinary projects, which is particularly pertinent to my experience.[318]

One practical challenge related to the impact of the finish of various tubings (i.e the smooth surface of PVC or the tacky surface of the platinum-cured silicone) on how easily they could be handled during the sampling process (i.e. when pulled through the knitted channels in the samples and garment prototype or stitched into a fabric without getting caught to a machine). These insights suggest that the interaction between tubing and yarns might be further considered in future design and development to ensure a smoother and more efficient production process. These findings are relevant to the future development of LCGs/LCVGs and for applications beyond specialised aerospace contexts.[319]

Another challenge related to coordinating between the two institutions during the initial stages of the project on matters that included finalising and completing engagement terms and contracts. It is crucial to acknowledge that different contributing institutions operate along different structures and timelines, which can make it challenging to work between them. Such difficulties illustrate that a considerable amount of the time and effort dedicated to this project is not evident or visually apparent in the material outcomes. However, analysis of the circumstances and conditions surrounding their creation and which have been fundamental in enabling and facilitating the HCRS, ICL and the RCA Textile Design department to come together in the first place reveals that previous interdisciplinary experience supports future interdisciplinary experience. The backgrounds of the ICL researcher and a senior member of the RCA's Textile Design department illustrate this point. The first had a BSc in electrical engineering from ICL and previous design experience; they completed an MA in Design at the RCA and made the connection with the RCA when recognising the skills that were required within the FAIR-SPACE project. The second brought several years of post-doctoral academic experience in the sciences to bear on understanding the requirements of ICL researchers and insight into RCA's capability to address them. Both were able to create bridges across the disciplines and bring a familiarity and ease of navigation to their differing structures, procedures and languages, in addition to supporting the development of the briefs. These examples highlight how individuals bring their specific expertise and experiences to bear on work with practitioners from other disciplines. These skills have been developed over time and through experience and have undoubtedly been instrumental in securing and facilitating the projects. This may be one of the defining characteristics of practitioners who work effectively in interdisciplinary and multidisciplinary smart textiles design environments. Experiences build fluency, and a certain degree of fluency is required for effective engagement across disciplines. Indeed, as one might observe: 'dexterity in interdisciplinarity is (l)earned.'[320]

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[318]Angela Last, 'Of Interdisciplinarity', in *Routledge Handbook of Interdisciplinary Research Methods*, ed. by Celia Lury and others, 1st edn (Routledge, 2018), pp. 197–208 (p. 202), doi:10.4324/9781315714523-30; Felicity Callard and Des Fitzgerald, 'Feeling Fuzzy: The Emotional Life of Interdisciplinary Collaboration', in *Rethinking Interdisciplinarity across the Social Sciences and Neurosciences*, ed. by Felicity Callard and Des Fitzgerald (Palgrave Macmillan UK, 2015), pp. 112–28, doi:10.1057/9781137407962_8.
[319] J.L.Leith and C.W.Hixon, *Development and Fabrication of an Advanced Liquid Cooling Garment*, p. 2.
[320] Ray Land, 'Crossing Tribal Boundaries: Interdisciplinarity as a Threshold Concept.', 2012, p. 3 <https://durham-repository.worktribe.com/output/1680593> [accessed 6 January 2025].

However, the nature of the research setting and my relationships with those within it are nuanced and not straightforward. Indeed, my working relationships at the HCRS, ICL fostered a sense of inclusion through the likes of everyday and social events, such as lunch and coffee breaks, as well as a Christmas dinner. I have been obliged to allay my anxiety about how I might write about my experiences without portraying the research in a way that might not ring true for those I worked alongside. This exposes a tension between a desire to please and a desire to accurately reflect my experiences. Here, I observe how, although the blurring of boundaries between professional and personal relationships in fieldwork is being discussed in the social sciences[321] alongside emerging discussions about interdisciplinarity as an affectively 'fuzzy' emotional domain,[322] they have not yet been explored within the field of textile design research and practice as it increasingly intersects with the sciences.

[321] Jamie Shenk, 'Personal and Professional Boundaries in Fieldwork', *University of Oxford's Social Sciences Blog*, 2021 <https://socsci.web.ox.ac.uk/article/personal-and-professional-boundaries-in-fieldwork> [accessed 31 December 2024].
[322] Callard and Fitzgerald, 'Feeling Fuzzy'.

Chapter 6. From textile designer to smart textiles designer — Synthesis and insights

6.1. Introduction

My research inquiry arose from a recognition that several inadequately addressed research gaps act as barriers to textile design's recognition as a critical discipline in science-led wearable smart textile design (Section 1.3.). This is despite textile design being uniquely positioned to support the holistic development of smart textiles.

After reviewing the literature (Chapter 2), I understood that I had to confront knowledge gaps between textile design and the sciences through hands-on making expertise. This could help achieve my aim of (a) engaging in the design and development of wearable smart textiles through interdisciplinary engagement with practitioners from scientific disciplines and (b) exploring the textile designer's role in the evolving field of wearable smart textiles. I also anticipated that addressing such gaps would be complex and challenging but also likely to engender valuable insights into this evolving field. To achieve my aims, I pursued the following objectives:

1. Identify textile methods and values that can enhance wearable smart textile design.
2. Examine science-led wearable smart textile research environments to integrate and observe design insights.
3. Critically reflect on the opportunities and challenges for textile designers contributing to the development of wearable smart textile design.
4. Provide a model for the role of practice-based textile design methodologies and mindsets in interdisciplinary projects.

These objectives were pursued within the context of practice-based research, where my practitioner-researcher identity shaped methodological choices (see Sections 1.1.1, 3.2.1 and 3.3.1.).[323]

In this chapter, I outline how these objectives supported me in achieving my aims. I shall, notably, detail the following four key adaptations to my practice (which emerged during the case studies) and explore them through practical examples and reflective analysis:

1. Expansion of roles and responsibilities.
2. Enhanced technical materials proficiency.
3. Broadened and application-focused design objectives.
4. Increased engagement with scientific disciplines.

Alongside these adaptations, I also highlight the systemic barriers that shaped them, synthesise insights into a transferable model for practice-based engagement and reflect on the evolving identity of

[323] Linda Candy and Ernest Edmonds, 'Practice-Based Research in the Creative Arts: Foundations and Futures from the Front Line', *Leonardo*, 51.1 (2018), pp. 63–69, doi:10.1162/LEON_a_01471; Sebastian Messer, 'Documenting Practice Research: Constraints and Opportunities', *Journal of Engineering Design*, 36.3 (2025), pp. 405–38, doi:10.1080/09544828.2024.2427558.

the smart textiles designer. Through my research journey and these adaptations, I also highlight three key findings:

1. The complexities of interdisciplinary engagement and how they shaped the evolving role of the textile designer within science-led smart textile contexts.
2. The need for a fluid mindset to bridge technical and creative domains.
3. The value of integrating tacit, experiential knowledge to enhance comfort, wearability and sensory appeal.

Note that the above adaptations were not merely procedural changes to my design process. They were, in fact, crucial to my research journey and its findings. In particular, they revealed a key insight from the research study: The transformative nature of my evolution from traditional textile designer to smart textiles designer was marked by an irreversible shift in my identity and mindset as a designer. Uncovering this demonstrated the nuance and complexity present in achieving my aims and objectives.

These adaptations and the new emotional territories I encountered and had to navigate are defining features of a smart textile design practice in the current context of the field. I have come to realise that this current context can be jarring and sometimes discomforting. This is due to the position it inhibits in the liminal space between disciplines and how disparate positions and paradigms come together. I shall draw on my semi-structured interviews to give additional insight into this environment. I also explore my transformation from textile designer to smart textiles designer through practical examples. These examples illustrate how my approach to practice has changed as a result of my engagement with the sciences and my application of textile methods and values to 'hard' challenge-led domains. I shall also explore this transformation through the theoretical lens of 'threshold concepts' (Section 3.2.1.).

Addressing my research objective of critically reflecting on the opportunities and challenges for textile designers contributing to the development of wearable smart textiles allowed me to understand interdisciplinarity as comprising two interconnected parts:

1. Research engagement with practitioners from other disciplines.
2. Introspective work focused on oneself, one's discipline and one's contribution.

This insight is supported by Valentine and colleagues' observation that new textile design methodologies that cross disciplinary boundaries often necessitate 'a personal journey', in which textile designers 'identify their own values through processes of making, which run parallel or are aligned to the needs of others.'[324] This dual approach was necessary to achieve an interdisciplinary perspective. Acknowledging that things do not always go to plan was also important. As Thompson and Thompson state in *The Critically Reflective Practitioner,*[325] the process of 'drawing out learning from our experience' and distilling useful learning points to guide future practice are salient features of reflective practice.

[324] Valentine and others, 'Design Thinking for Textiles: Let's Make It Meaningful', p. 966.
[325] Sue Thompson and Neil Thompson, *The Critically Reflective Practitioner* (Bloomsbury Publishing, 2023), p. 12.

Other disciplines may find the physical outcomes produced during my research study incomplete because those outcomes have not yet achieved the functionality of wearable smart textiles. I have, nonetheless, come a long way in terms of providing a means for developing key insights for the textile design discipline and the wearable smart textile field. I had to navigate numerous compromises and discomforts. And, I must acknowledge their part in interdisciplinarity and in revealing both what is required of a textile designer and relevant facets of the approach required.

6.2. The complexities of interdisciplinary engagement and how they shaped the evolving role of the textile designer within science-led smart textile contexts

Although interdisciplinary engagement can benefit both the fields of textile design and wearable smart textiles, my readings (Chapter 2) suggested that achieving this might not be straightforward. As discussed in Sections 4.3.3 and 5.4.2, I notably faced difficulties in finding research environments designed to support the conditions for the kind of interdisciplinarity described in the literature. Indeed, my engagement as a textile designer within the case studies can best be described as multidisciplinary. That said, my experiences reveal that the prevailing theoretical base and research practices in science-led smart textiles research domains are not yet conducive to interdisciplinary work. This is despite the fact that such domains increasingly welcome textile design input. My experiences consequently reveal a disparity in the value attributed to textile design knowledge beyond the practical application of textile design making skills. This highlights a challenge for the application of 'the full extent of the textile designer's capital' [326] within the current landscape of smart textile design.

As discussed in Sections 4.3.3 and 5.4.2, systemic barriers include fragmented engagement across disciplines, limited availability and involvement of scientific project contributors, constraints on time and funding and the dominance of scientific and engineering knowledge frameworks. However, as highlighted in Section 2.2., these knowledge frameworks do not account for the importance of embodied knowledge and reflective practice in the design and development of wearable smart textiles; this leads to an undervaluation of textile design's contributions. As a result, in order to contribute in the field, I had to travel further into the domain of the scientific researchers than they travelled to meet me, and, as part of this experience, make adaptations to my practice, approach and thinking as a textile designer. For example, by increasing my technical understanding of materials, I ensured that textile sampling in my case studies was closely aligned with intended applications, achievements already documented in the technical literature and what was practically feasible. This targeted approach helped me to avoid tangents and maintain focus on the goals at hand. In CS2, I familiarised myself with the tubing distribution layouts used in wearable thermoregulation garments and ensured tubing dimensions – such as internal and outer diameters – were compatible with the digital embroidery machine's programming requirements (Section 5.3.1.3).

I suspect that this challenge can be attributed to the entrenched systemic obstacle that is rooted in the capitalist, neoliberal context in which we find ourselves.[327]This context prioritises productivity and

[326] Lerpiniere, 'Value Definition in Sustainable (Textiles) Production and Consumption', p. 85.
[327] Isabelle Stengers, *Another Science Is Possible: A Manifesto for Slow Science* (Polity Press, 2018).

efficiency above all else and is evident in the 'publish or perish' culture characterising scientific research, which pressurises researchers to rapidly produce quantifiable outcomes. During the case studies, I observed this culture first-hand. I found myself immersed in research environments where results-oriented project structures and highly technical objectives left individuals juggling multiple project deadlines. This left little time for the exploratory and reflective practices commonly found in textile design approaches (Section 3.3.1). One of the scientific project contributors I worked with noted the following in this regard:

> *The problem is that I work on multiple projects and I cannot concentrate 100% on a project….to have the…….progress that I would have liked to have, so I have been working on many projects at the same time and everything progresses slowly…emmm......it would have been nice if I could dedicate 100% of my time on this specific project…*[328]

These systemic barriers I encountered, such as an overemphasis on productivity and efficiency, shaped project structures and priorities, restricting opportunities for open exploration and material experimentation. These limitations hinder the emergence of the kind of serendipitous outcomes that are central to creative approaches, which in turn are fundamental to the pursuing of sensory enhancement. These barriers align with the research gaps outlined in Chapter 2 (p. 25) and highlight the complexities textile designers face when contributing to the development of wearable smart textiles in scientific research environments. Despite these complexities and constraints, I believe that I demonstrated textile designers' critical role in the field while highlighting what is required of them to meaningfully contribute and advance the field. It is possible for a designer to take steps towards bridging knowledge domains through hands-on making, even when systemic barriers present imbalances in value attribution and hinder interdisciplinary engagement.

I now present these adaptations through examples from the case studies undertaken in my research. The goal is to highlight how they manifested differently within the case studies. I further highlight how these case studies offer different ways of approaching and achieving my research aims and objectives.

6.3. Adaptations to practice

Given the above-mentioned complexities, I drew on the textile design disciplines inherent 'adaptability.'[329] This was to align my practices with technical goals and effectively support project outcomes. I also applied my hands-on making expertise to bridge science/engineering and textile design, specifically in the previously uncharted science-led research areas of wearable sensing for nuclear decommissioning operators and astronaut thermoregulation.

As discussed in Section 3.3.2., hands-on making expertise within textile design typically manifests through 'sampling' – the 'signature pedagogy' of the discipline – rooted in the 'know-how'

[328] Claire Miller, 'Dataset Accompanying Thesis "An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines"' (RCA research repository, 2024), p. 8, doi:https://doi.org/10.60624/M8P1-YA33.
[329] Coulter, 'The Designers Leap: Boundary Jumping to Foster Interdisciplinarity between Textile Design and Science'.

learning mode. Analysis of practice in this study indicates that while this ‘maker’ role has remained integral to my evolving position as designer in both case studies, its expression has differed in terms of textile techniques, technical influences and the required learning processes. These differences were shaped by the individual case studies’ unique characteristics and technical requirements (i.e their differing contexts, application-areas, material requirements and scientific project contributors’ expertise). This highlights the need for textile designers to align their practices with a variety of technical goals and interdisciplinary objectives:

1. ‘Making photonic textiles’(Chapter 4): In this project, I focused on designing knitted textile samples for nuclear decommissioning operators’ wearable innersuits. This necessitated integrating and securing POF as OFS in knitted textiles for wearable sensing. This, in turn, required balancing technical functionality with the sensory and tactile experiences crucial to comfort and wearability.
2. ‘Designing textiles for integrated networks of fluidic heating and cooling’ (Chapter 5): In this project, I focused on designing embroidered and knitted innersuit samples for astronaut thermoregulation. This required creating knitted and embroidered textile samples with integrated channels for threading polymeric tubing, which enhances seamless thermal comfort.

These varied requirements or influences shaped four key adaptations to my practice— adaptations which, in turn, shaped my transition from textile designer to smart textiles designer. They were especially important to my making, learning and contributing:

1. Expansion of roles and responsibilities: *Incorporating new methods and activities in my position as designer. These go beyond methods and activities typically associated with conventional textile design practices.*
2. Enhanced technical materials proficiency: *Developing enhanced materials proficiency relative to those materials’ technical attributes.*
3. Broadened and application-focused design objectives: *Extending design objectives beyond sensory/aesthetic considerations to include objectives that address technical functionality and application-focused requirements.*
4. Increased engagement with scientific disciplines: *Facilitating translations between the scientific/engineering and textile design knowledge domains.*

I have broadly outlined these adaptations in Table 6.1. I also highlighted how their expressions have varied between the two projects, even if they are consistent across both case studies.

Table 6.1. Expressions of my adaptations to practice as a designer within the two case studies

Case study	Expansion of roles and responsibilities	Enhanced technical materials proficiency	Broadened and application-focused design objectives	Increased engagement with scientific disciplines
1: Making photonic textiles	Maker (textile sampling: ‘know-how’); Desk-based researcher (literature reviews: ‘know-what’); Facilitator/co-researcher (workshop: ‘know-with’).	Gained knowledge on integrating POFs as OFSs in knitted textile samples ensuring secure integration without compromising a POFs technical functionality.	Combined sensory and tactile material considerations to securely integrate POFs, thereby maintaining their functionality as OFSs.	Engaged with photonics and electronics engineers during workshops; Reviewed scientific literature to inform design decisions.
2: Designing textiles for integrated networks of fluidic heating and cooling for astronauts’ inner suits	Maker (textile sampling: ‘know-how’); Desk-based researcher (literature reviews: ‘know-what’); Embedded researcher (semi-structured interviews ‘know-with’ and show-and-tell meetings ‘know-with’).	Gained knowledge related to tubing behavior and its integration as a thermal comfort system in wearable thermoregulation garments.	Addressed sensory and tactile comfort while designing textile samples incorporating integrated flexible tubing layouts. The goal was to optimise thermal comfort and wearability for astronauts’ innersuits.	Worked as an embedded researcher at HCRS, ICL; Conducted semi-structured interviews and participated in show-and-tell meetings with project contributors and research participants; Reviewed scientific literature to inform design decisions; Co-published a book chapter with scientific researchers from HCRS, ICL.

6.3.1. Expanding roles and responsibilities

The roles and learning modes I adopted reflect an approach that is not typically cultivated in conventional textile design processes. This resulted in a fundamentally different design process from the one instilled in me through my textile design training. It also marked a departure from the approaches to thought and practice found in my traditional role as 'maker' and the predominantly 'studio-based' practices prevalent in textile design and education.[330] This role relied heavily on hands-on material experiences to develop materials knowledge – features of the 'know-how' learning mode and central to the textile practices outlined in 3.3.1.– which I have honed and developed over recent decades. Previously, I considered this mode of working[331] to be integral to my identity as a textile designer.

Table 6.1. highlights the new roles and responsibilities that I took on, including 'desk-based researcher' to gain 'know-what' or propositional understanding of materials and application areas through literature reviews. Using both 'know-with' and 'know-how' learning modes, I deepened my understanding of previously unfamiliar materials. This occurred through group demonstrations and workshop formats across textile design and the sciences and was undertaken in my role as 'facilitator and co-researcher' and. In CS1, these expanded roles were crucial in enhancing my technical proficiency, specifically as it relates to potential POFs as wearable sensors (Appendix B). This included exploring their functional and sensorial capabilities and developing a comprehensive understanding of the challenges nuclear decommissioning operators face (4.1; Appendix J).

Similarly, in CS2, I sought to understand the unique and domain-specific technical challenges associated with thermoregulation for astronauts and to identify areas for textile design intervention (Appendix S). Attempting to achieve greater levels of interdisciplinarity than were obtainable in CS1, I built on these roles and added 'embedded researcher.' This aligned with my second objective by facilitating access to science-led research environments, where I could examine disciplinary approaches and integrate design insights through frequent engagement with scientific teams (refer to Figure 5.3.). Activities such as, 'show-and-tell' meetings (once again drawing on the 'know-how' learning mode) and sourcing textual and scientific materials from scientific databases accessible through the ICL library (a feature of my 'embedded researcher' role) supported this process. I also conducted semi-structured interviews. There, I adapted the 'know-with' learning mode to gain additional insights about engagement within the field.

By taking on new and unfamiliar roles, I have taken the necessary steps to intellectually and physically connect these technical and creative realms (as in CS2) by traversing between the RCA and ICL. In doing so, I have also supported my first objective of identifying the textile methods and values that can enhance wearable smart textile design through undertaking the research necessary for this

[330] Sarah Kettley, *Designing with Smart Textiles* (Fairchild Books, an imprint of Bloomsbury Publishing, Plc, 2016), p. 40, doi:10.5040/9781474222259.
[331] Traditional textile design methods are heavily reliant on hands-on and sensory experiences and ordinarily begin with tactile and visual material to guide inspiration and the design direction. These might include filling sketchbooks with drawings and collected materials to create mood boards, nurturing an overall 'look and feel' for the project (Wickenden, 2020; Clarke, 2011; Briggs-Goode and Townsend, 2011). These methods are drawn on by the textile designer to emphasise the visual and tactile qualities of materials (Gale and Kaur, 2002, pp. 37–39)

identification. Engaging with technical materials challenges through hands-on making has, in turn, supported the project's progression.

6.3.2. Enhanced technical materials proficiency

I mentioned (Section 2.1.1.) how smart functions (e.g. electrical, thermal, or absorption properties) can be integrated into yarns and fibres (i.e woven into textiles). This offers new dimensions to traditional material properties. That said, dynamic properties (e.g. the ability to conduct electricity) are often not immediately visible or tangible. This means that hands-on textile design methods for gathering materials understanding have had to be supplemented by other methods to fully grasp their working mechanisms and thus potentials and limitations in specific, application areas. The need to bridge the gap between conventional and smart material understanding led to the second adaptation to my practice: enhanced technical materials proficiency. This adaptation focuses on the technical knowledge or 'know-what' I had to accumulate to align technical functionality with sensory and tactile experience in the two case studies.

Awareness of the steep learning curve I faced influenced my approach to shaping the initial design direction. I also turned to textual and scientific materials to ensure that my materials were developed in line with projects' functional needs. These were sourced either independently, through scientific project contributors, or as in CS2, as mentioned above, through scientific databases at ICL (as in CS2). This initial technical understanding was essential because there were certain things I simply *had* to know before I could begin making and engaging with the 'soft' in these domains. A textile designer interviewee, involved in the FAIR-SPACE project expressed a similar point. She noted the following:

> *That's been pretty new—reading a lot of literature—because I hadn't really referred to papers in that sense…I've done a lot of like design research, but I haven't looked at papers…So…a lot of the design research I used to do—the books I would look at and refer to—they were a lot like reference books in terms of… looking at new ideas in a more abstract way, whereas now, when you are reading papers, everything starts to get more practical and technical."*[332]

This enhanced proficiency influenced both the design direction and subsequent decisions, such as which textile processes and techniques I should explore. In both cases, these decisions supported my primary objective of identifying textile methods and values that can enhance smart textile design. To understand pertinent design capabilities and limitations, I needed to develop sufficient technical understanding of both the polymer optical fibres used in CS1(Appendix H) and the polymeric tubing used in CS2 (Appendix M). Here are two examples:

- In CS1, understanding the stiff and brittle nature of POFs and their minimum bend radius, was crucial for physically working with them, while keeping efforts focused. This immediately rendered several knitted textile processes unsuitable for their integration (see Appendix B). It also indicated that I should focus on stabilising and securing POFs in the

[332] Miller, 'Dataset Accompanying Thesis "An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines"', p. 24.

textile structure. This led me to explore integrating heat-fusible yarns in a way that minimally impacts fabric handle.
- In CS2, I developed an understanding of (a) polymeric tubing, its behaviour and distribution layouts and (b) how these factors interrelate in the context of thermoregulating wearable innersuits.

This technical knowledge not only supported me in refining my material choices and techniques. It also helped me recognise areas that could benefit from textile design engagements before the design process. This supports Valentine and colleagues' observation that projects bridging textile design and science (e.g. smart textiles) require a significant amount of time in the concept development phase due to a shift in functionality and the making process.[333] By engaging in science-led research environments, I was able to observe and integrate these insights. This contributed to my second research objective (examine science-led wearable smart textile research environments to integrate and evaluate design insights).

Additionally, this adaptation to my practice provided the evidence necessary to convey my developing knowledge and understanding in a co-authored book chapter[334]and a literature review. This, in turn, illustrates how I was actively taking on new ways of making and thinking and incorporating them into my practice. Moreover, in both case studies, engaging with smart textile literature further highlighted my critique outlined in Section 2.2, specifically the lack of sensory understanding that existed in domains where materials were developed and applied. This supported my second research aim (explore the textile designer's role in wearable smart textiles). It did so by highlighting how as a textile designer I have imbued these sensory and tactile qualities in wearable smart textile design. It also reinforced my second research objective (integrate and observe design insights by integrating tactile and wearable considerations and to reflect on the opportunities and challenges for textile designers contributing to this field). In gist, enhancing my technical materials proficiency, I have been able to take steps towards bridging creative and technical domains. This, in turn, demonstrates both textile design's critical role and its complexity in this evolving wearable smart textile field.

6.3.3. Broadened and application-focused design objectives

The third adaptation to my practice addresses my second and third objectives. It has also broadened my design objectives to prioritise practical application-focused outcomes. Traditionally, this approach has aligned more closely with disciplines like industrial design (where the end product and its user are central considerations) or fashion (where the end product is considered through constructs like the 'muse'). Textile design has, in contrast, traditionally focused on broader receptive end markets with more emphasis on sensory and aesthetic experiences than on specific, application-driven outcomes.

Across both case studies, this third adaptation has involved extending my design objectives' scope to include technical functionality alongside sensory and tactile considerations:

[333] Valentine and others, 'Design Thinking for Textiles: Let's Make It Meaningful', p. 966.
[334] Khan and others, 'Physiological Adaptations in Space and Wearable Technology for Biosignal Monitoring'.

- In CS1, this third adaptation was primarily concerned with immediate material challenges related to securing and stabilising POFs as OFSs, with considerations of comfort and wearability. Despite the POFs rigidity, I sought to secure them without compromising their functionality, while ensuring that their handfeel and drape were maintained.
- In CS2, these objectives included further considerations related to textile and garment construction methods (Section 5.2). The importance of this is also recognised in CS1.

Reflective sampling and incremental changes allowed me to consider both (a) the tactile and sensory properties necessary for wearability and (b) technical aspects like fluidic tubing integration (i.e. integrating tubing without puncturing it) and its distribution and alignment against the skin for optimal thermal comfort and the tactile and sensory properties necessary for wearability. These examples demonstrate the following:

1. How ‘soft’ exploratory and creative textile approaches (including methods like sampling) can be repositioned and embedded into the highly technical, application-driven wearable smart textile field. This repositioning seeks to ensure that experiential qualities (e.g. texture, handle, drape and appearance) are thoughtfully considered and preserved alongside technical objectives. This can, in turn, contribute to improved comfort, wearability, and sensory engagement.
2. An application-focused approach (made possible by my hands-on expertise) can bridge technical and creative domains. This reflects the evolving role of the textile designer, the project's longer duration and the ongoing transformation of my practice from traditional to smart textile design.

One of my textile design interviewees made a similar point:

> *So I think the application has become a really strong factor now. It's like how is this thing that you are making being applied and used?* [335]

The above examples demonstrate how I considered a wider array of attributes, beyond sensory and tactile considerations, as I broadened and focused my design objectives to include considerations relevant to real-world applications: i.e., in CS1, enhanced moisture-wicking merino yarns were placed in the rows surrounding the reading points of the POFs to prevent OFS slippage against the skin, which could result in inaccurate readings. That said, the steep learning curve necessitated by enhancing my technical materials proficiency meant that I had to rein in an aspect of my identity related to sensory/aesthetic understanding. Sensory and tactile understanding exist within the constraints of technical functionality, which is currently the wearable smart textile domain’s primary focus. Although my initial intention was to emphasise both areas, scientific contributors engaged in the project considered the functional and technical aspects to have a higher value during the sampling process.

[335] Miller, ‘Dataset Accompanying Thesis “An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines”’, p. 24.

6.3.4. Increased engagement with scientific disciplines

My fourth adaptation (increased engagement with scientific disciplines) underpins the three adaptations mentioned above. Due to its prominent position in my thesis, it warrants recognition as a standalone adaptation to my practice. This adaptation directly supported me in addressing my aim of engaging in the design and development of wearable smart textiles through interdisciplinary engagement. It allowed me to explore the textile designer's role in the evolving field of wearable smart textiles and my objective of examining science-led wearable smart textiles research environments to integrate and evaluate design insights.

In both CS1 and CS2, I engaged with scientific disciplines and contexts that were previously unfamiliar to me. This involved working with optics and photonic engineers (CS1) and robotic and electronic engineers (CS2). There were several interaction points across both case studies (refer to Figure 4.14 and Figure 5.14). These included the interdisciplinary workshop format. CS1 (Appendix C) involved enabling bi-lateral knowledge exchange related to the use of POFs as wearable sensors. In CS2 – where I was an embedded researcher at the HCRS, ICL – I had further opportunities for engagements across disciplines. These included 'show-and-tell-meetings' for sharing technical literature, engaging in discussions and gathering feedback from scientific project contributors. Such exchanges enabled me to assimilate technical 'know-what'. They ensured alignment with application-specific goals, which I later incorporated into the textile design and development process through sampling. When designing the tubing layout, for example, I took on board information scientific project contributors provided. This information is related to, for instance, the necessity for a 'snaking' pattern to increase surface area for the fluidic tubing system. When designing the garment prototype, I selected a full-sleeve design so that the thermoregulatory device (designed by scientific researchers and intended to be worn on the wrist) could connect directly to the garment prototype.

My further development of these samples into a garment prototype (Appendix R), demonstrates:

- A synthesis of technical 'know-what' gained during engagement with scientific disciplines;
- The possibility of independent working (even during engagements across disciplines);
- A progression in my confidence, specifically when it came to my bespoke role and the complexity of the challenges I was prepared to take on (CS1 only dealt with samples and CS2 involved moving on to a garment prototype).

In addition, creating the garment prototype demonstrated my response to the recognition gained in CS1: For optimal development in wearable smart textiles, one must simultaneously consider physical material properties, the development of textile structures and garment construction methods.

In this section I have described relevant adaptations to my practice and highlighted how they address my aims and objectives. To present these connections in a more accessible format, I have also visually mapped them in the below Figure 6.1:

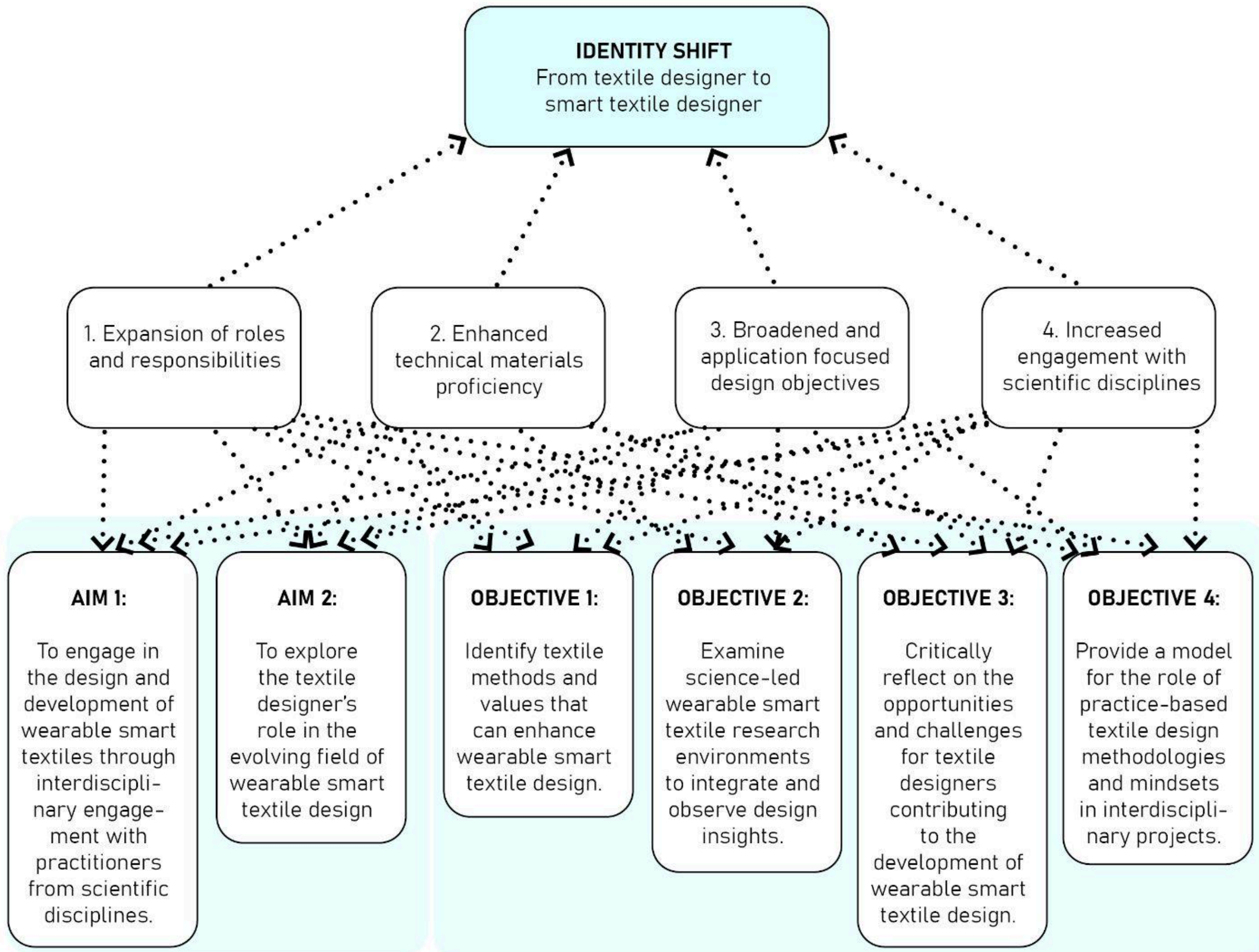

Figure 6.1. *Adaptations made to my practice during my evolution from textile designer to smart textiles designer, mapped against the aims and objectives of my research.*

6.3.5. Summary of adaptations

Although I have described the above adaptations separately, it is important to highlight that they are interrelated and overlapping. Combined, they reflect the fundamental changes to my practice which have taken place as I transitioned from textile designer to smart textiles designer. They also demonstrate the textile designers' critical and evolving role in interdisciplinary, but science-led, contexts. The adaptations' analysis, and the individual examples from the case studies chosen to illustrate them, highlights how the latter offered different approaches to addressing both (a) my aims and objectives and (b) the research gaps outlined in Sections 1.3 and 2.2.

I have recognised that my journey into the smart textile domain as a textile designer necessitates fundamental adaptations to conventional processes, practises and thinking in textile design. It is, however, important to acknowledge that this insight has already been made in the literature. Smart textiles designer and researcher Rachel Wickenden, for example, has done so in her doctoral thesis on the design of e-textiles (a subsection of smart textiles, for interior spaces). She describes how working in the technically 'dominated' field requires changing traditional design processes.[336] If so, then the adaptations I described above might be integral to working in the smart textile design space. Yet, although Wickenden recognises that textile designers must make these changes as they transition into working in smart textile domains, she does not discuss such changes' impact on the textile designer's broader identity. This includes the mindset and internal realm of someone venturing into these new research territories. It also relates to a sense of sacrifice required, especially when it comes to (a) the emotional territories that must be navigated and (b) some of textile design's sensorial aspects (viz. my study does not adequately explore the visual because the primary focus is on tactile comfort and wearability).

6.3.6. The impact of these challenges to the textile designer identity and mindset

My engagement with science-led research domains has necessitated prioritising technical and functional elements over sensory experience. This has led me to adopt a somewhat targeted and rational approach to knowledge construction and dissemination. As before, this shift has challenged my established identity as a textile designer. It has necessitated that I set aside my creative identity – my 'sensorial self' – to a certain extent and adopt a more functional, application-focused perspective – an observation which was echoed by one of my interviewees working within the smart textiles field:

> *So I feel like now there is no poetic or abstract element to it, right now at least, because it's like a technical product that you are developing...*[337]

The ways I have worked during the exploratory case studies and the adaptations made to my practice have pushed me to develop an understanding of new value systems and balance these with my existing understandings of textile design. This has broadened my understanding of how technical parameters can at once expand textiles' possibilities. They do so by offering new material properties [338] and thus opportunities for 'sensory material aesthetics,'[339]even if they can concurrently restrict the space for such expressions. In a way that was not possible before engaging in this study, I now recognise that textiles designers must jointly consider multiple, and sometimes conflicting, objectives during the research process. My progression toward a more rational mindset was also required to find balance, and it is evident in the work itself. An example is what was produced during the preliminary study (Appendix A, Figure A.2). Although not plainly demonstrative of how the samples might be used within an applied

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[336] R. Wickenden, 'Rethinking E-Textile Design: Process, Purpose and Sustainability' (unpublished PhD thesis, Nottingham Trent University, 2021) <https://irep.ntu.ac.uk/id/eprint/45291/> [accessed 3 November 2023].
[337] Miller, 'Dataset Accompanying Thesis "An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines"', p. 40.
[338] Ayman Fathy Ashour, 'DESIGN AND SMART TEXTILE MATERIALS', 2021, pp. 145–51, doi:10.2495/MC210161.
[339] University of Borås, School of Textiles and others, 'Introducing Sensory-Material Aesthetics in Textile Design Education', *Revista Diseña*, 20, 2022, doi:10.7764/disena.20.Article.7.

context, they are more evocative and sensorially compelling than what was produced at later stages (see e.g. Figure 5.5b), which had a stronger connection to scientific domain-specific applications.

Such a shift makes it difficult to sustain initial priorities and positions. This illuminates the point at which sacrifices in the sensory sphere might emerge. These can potentially stifle the creativity that is essential to innovative outcomes by marginalising other valuable perspectives. That said, such adaptations seem integral to working in the smart textile design space and are fundamental to a 'purpose-led' and sustainable approach to design.[340] Upon reflection, I might have better considered how to hold on to a space for exploring sensory experiences at the outset. This is significant. My practice demonstrates the value of integrating tacit experiential knowledge to enhance comfort, wearability and sensory appeal in smart textiles. It does so by repurposing and embedding soft textile thinking and textile sampling into new fields of practice. Yet, it also reveals the dominance of technicality and functionalist aesthetics in current smart textile design. As fashion and textile author and researcher Sarah Braddock Clarke notes[341], such aesthetics are reminiscent of the modernist design principle '*Form follows function.*' Here, pleasure is derived from usefulness and anything that is unnecessary is eliminated.

My wandering into unfamiliar research domains involved periods of low confidence, frustration, disappointment, excitement and anticipation. This emotional navigation highlights how the trajectory entails both losses and gains. The journey through the complexities of such a change (or 'threshold concept'[342]) involves traversing the 'liminal space' between two intellectual realms. This space is fraught with both the challenge of uncertainty and experiencing myriad conflicting emotions and feelings. This has contributed to both the research process and its findings. The 'push and pull' of these emotions created a pervading sense of uncertainty, which I now consider a crucial feature of my evolution from textile designer to smart textiles designer.

This aligns with Callard and Fitzgerald's view[343] of interdisciplinarity as not only 'hard, intellectual and methodological labour' but also emotional work—work that is 'driven by the presence of (and requirement to manage) many different kinds of feelings, not all of them joyful.' Callard and Fitzgerald thus suggest that emotions are not merely peripheral. They are, instead, integral to the interdisciplinary research process. This is because, by addressing and acknowledging them, researchers can enhance their ability to navigate complex interdisciplinary spaces and foster productive collaborations and outcomes.[344] However, although these aforementioned feelings can be a facet of any creative endeavour, multidisciplinary and interdisciplinary projects further complicate this range of emotions by posing a more extreme challenge to the researcher's sense of identity.

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[340] Wickenden, 'Rethinking E-Textile Design'.
[341] Sarah Elizabeth Braddock Clarke, 'Clothing+embedded Technology: Past Challenges, Future Opportunities', in *Smart Clothes and Wearable Technology (Second Edition)*, ed. by Jane McCann and David Bryson, The Textile Institute Book Series (Woodhead Publishing, 2023), pp. 3–37 (p. 8), doi:10.1016/B978-0-12-819526-0.00007-2.
[342] Meyer and Land, 'Threshold Concepts and Troublesome Knowledge 1 – Linkages to Ways of Thinking and Practising'.
[343] Felicity Callard and Des Fitzgerald, *Rethinking Interdisciplinarity across the Social Sciences and Neurosciences* (Palgrave Macmillan UK, 2015), p. 112, doi:10.1057/9781137407962.
[344] Felicity Callard and Des Fitzgerald, 'Feeling Fuzzy: The Emotional Life of Interdisciplinary Collaboration', in *Rethinking Interdisciplinarity across the Social Sciences and Neurosciences*, ed. by Felicity Callard and Des Fitzgerald (Palgrave Macmillan UK, 2015), pp. 112–28 (p. 13), doi:10.1057/9781137407962_8.

This transformed view aligns with both the preconceived image of the explorer, who might be expected to return from their travels irreversibly changed and with a new outlook as a result of their exploits, and with threshold concepts, where 'as a consequence of understanding a threshold concept, there may thus be a transformed internal view of subject matter, subject landscape, or even worldview.[345]'

6.3.7. A model for the role of practice-based textile design methodologies and mindsets in science-led interdisciplinary projects

In response to the challenges and adaptations described above, and addressing my fourth research objective, I have developed a model (see Figure 6.2) for the role of practice-based textile design methodologies and mindsets in interdisciplinary projects. The central line represents my journey as practitioner–researcher, navigating the research landscape with a fluid mindset – exemplified in my case through the metaphorical practitioner-researcher identity of the 'material explorer.' This flexibility was essential for adapting practices outlined in Section 6.3 and in Figure 6.2 to work within the systemic barriers identified in Section 6.2, such as limited engagement of scientific project contributors, the dominance of technical priorities and constraints of time and funding. It also involved navigating the uncertainty inherent in this space and the change in designer identity that occurred as a result. This was not only about adapting practices and repurposing the 'signature pedagogy' of the textile design discipline, but also about recognising that my identity as a designer was shifting through the process and that this transformation itself became a central part of the model. Rather than a fixed sequence, the model in Figure 6.2 shows an adaptive process. Table 6.2, presented below, offers illustrative examples from the case studies of how barriers were addressed in practice.

This navigation of these challenges – both systemic and emotional – informs the model, which is intended as a flexible guide that is both scalable and transferable, able to support projects of varying size, duration and disciplinary mix. One might employ it in adjacent fields, such as smart textiles for rehabilitation, where garments must balance therapeutic functionality with patient comfort. Here, the model could guide designers to anticipate this tension at the outset, work reflexively through the sampling process to integrate these aspects and resolve conflicts during the design process. Similarly, in performance-monitoring sportswear, where the technical demand for precise sensor placement can conflict with breathability and unrestricted movement, the model could support balancing technical and experiential priorities so that prototypes are adjusted to secure sensors without compromising comfort or performance. In both contexts, functional reliability is achieved without neglecting long-term wearability. More broadly, the model is operationalised by recognising systemic barriers, developing targeted adaptations and moving fluidly between Schön's reflection-*in* and *-on action*[346] throughout the textile sampling process, to sustain progress, balance multiple design considerations and integrate tacit, experiential knowledge[347] within technically driven contexts. As part of this, one could also adopt, as I have, a metaphorical practitioner–researcher identity to lean into the explorative aspects of working across boundaries.

[345] J H Meyer and R Land, 'Threshold Concepts and Troublesome Knowledge 1 – Linkages to Ways of Thinking and Practising', in *Improving Student Learning – Ten Years On* (OCSLD, 2003), p. 1.
[346] Schön, *The Reflective Practitioner*, p. 172.
[347] Polanyi, *The Tacit Dimension*, p. 4.

Anchoring the process in making ensures that tacit and experiential knowledge remain central, even when technical priorities dominate. By iterating between reflection, adaptation and practice, the practitioner–researcher can respond dynamically to changing project conditions, supporting the integration of practice-based methodologies and the generation of innovative outcomes. This framing positions the practitioner–researcher at the centre of the process and highlights making as both the anchor and the driver of innovation within a sustained, reflective negotiation. Thus, the model demonstrates how practice-based textile design can act as both a method and a mindset: a way of negotiating constraints while preserving the embodied expertise that textile designers can uniquely contribute to interdisciplinary innovation.

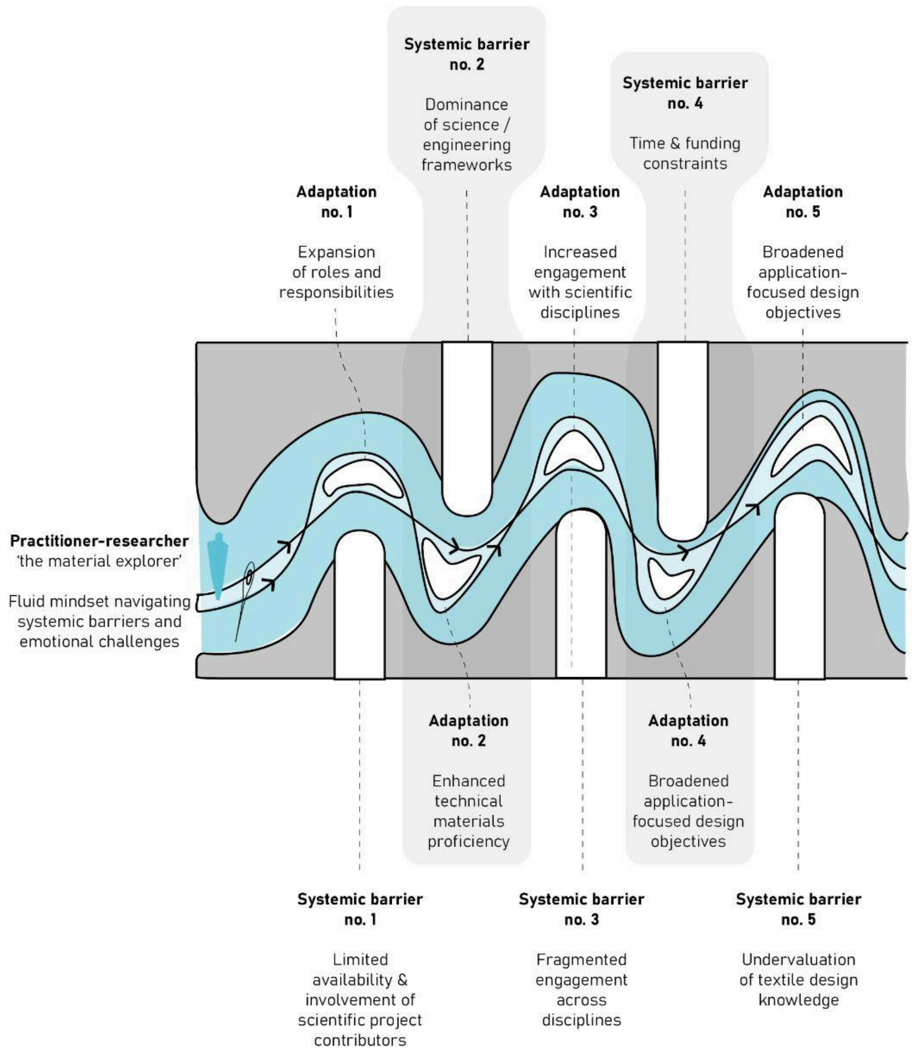

Figure 6.2. *A model for practice-based textile design engagement in interdisciplinary smart textile projects.*

Table 6.2. Illustrative examples of barriers, adaptations and demonstrations of a fluid mindset integrating tacit & experiential knowledge (aligned with Figure 6.2)

Barrier	Adaptation	Example from Case Studies	How This Demonstrates a Fluid Mindset Integrating Tacit & Experiential Knowledge
Limited engagement of scientific project contributors	Expansion of roles and responsibilities	CS2: When the first brief stalled due to low engagement, I shifted between roles, as maker and facilitator, to progress an alternative design pathway.	Flexibility to adapt my role in response to changing circumstances, drawing on tacit knowledge of materials to maintain momentum and integration with the broader project goals.
Dominance of science and engineering knowledge frameworks	Enhanced technical materials proficiency	CS1: I developed knowledge related to the technical constraints of POFs, specifically their minimum bend radius and handling requirements and adapted my design approach to support their functionality.	Flexibility to integrate new technical understanding with existing experiential knowledge of materials and making, enabling design solutions that respected functional limits while retaining textile values.
Fragmented engagement across disciplines	Increased engagement with scientific disciplines	CS2: I embedded myself for six months at the HCRS, ICL, drawing on experiential knowledge from CS1 that limited engagement across disciplines could hinder progress, to deepen engagement and strengthen interdisciplinary potential.	Flexibility to adapt my working patterns in response to challenges, integrating experiential understanding from CS1 to foster deeper engagement and interdisciplinary potential.
Constraints of time and funding	Broadened and application-focused design objectives	In CS1, I used moisture-wicking yarns around the POF reading points to prevent slippage against the skin, ensuring accurate readings while retaining comfort and wearability within project constraints.	Flexibility to integrate experiential understanding of wearability with tacit textile construction knowledge, adapting objectives to meet functional requirements within time and resource limits.
Undervaluation of textile design knowledge	Broadened and application-focused design objectives	In CS2, I aligned tactile and sensory qualities with technical needs, such as a full-sleeve design enabling direct device connection, so these aspects contributed to functional outcomes.	Flexibility to integrate experiential understanding of sensory and tactile qualities with tacit textile design knowledge, aligning these with application-focused outcomes valued by scientific project contributors.

6.4. The Evolving Identity of the Smart Textiles Designer

I have elucidated how I adapted my modes of working to include those that were previously unfamiliar alongside more familiar textile design approaches (6.2). This highlights the kind of research that must take place in these domains as they currently stand if one wants to learn, make and contribute as a textile designer. I have also demonstrated an application of the open and adaptable approaches found in textile design processes, practices and thinking to the wearable smart textile domain (Section 2.2.1.2). Bringing such approaches to this field has been essential. This is because it was impossible to predict which approaches or roles I should adopt in attempting to satisfy the needs of the individual projects or familiarise myself with them before undertaking the exploratory case studies. These approaches and roles emerged in response to individual projects' progression and needs. This means that I could not become familiar with them beforehand or operate with any degree of certainty throughout the process.

The smart textile domain's particularly wide scope makes it difficult to anticipate what one might encounter. Partners, projects, and intellectual territories vary greatly, and several moving parts are in play at any given time. One cannot commence projects with fixed expectations. One must, instead, be open and willing to navigate changing roles and project goals. This also serves as a response to Janet Coulter's[348] call for textile designers to bring the 'inherent adaptability' of their approaches to the smart textiles field as they 'boundary jump' between familiar design territories and scientific domains. Coulter highlights the importance of textile designers being willing 'to step outside of personal comfort zones' and embrace new ideas, approaches and collaborations. This adaptability is crucial when effectively navigating interdisciplinary smart textiles domains and contributing to innovative solutions.[349]

Bringing such approaches to the field reflects a broader evolution, one that is taking place within textile design research and practice. Here, textile design approaches are being increasingly theorised in textile design research (Chapter 2, p.28) through their application to global challenges posed by new technologies and sustainability issues. Lean,[350] for instance, draws on textile design approaches to improve our understanding related to textile designers' evolving role in interdisciplinary research that focuses on the materialisation of intangible data. This bridges gaps between traditional textile practices and modern technological applications. That said, Lean does not engage with 'making' in these fields (as I have done here). Although not specifically in the smart textiles field, Cathryn Hall and Rebecca Earley's research[351] emphasises the importance of versatility in the textile designer's role when acquiring knowledge to tackle real-world problems. My navigation of new roles (such as 'desk-based researcher' and 'facilitator/co-researcher') related to participating in, and contributing to, the smart textile design field also reflects the finding of Valentine and colleagues.[352] As before, these scholars maintain that textile designers' responsibilities evolve in response to global challenges posed by new technologies and sustainability issues. This evolution towards a wider material knowledge base and versatile skills, through

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[348] Coulter, 'The Designers Leap: Boundary Jumping to Foster Interdisciplinarity between Textile Design and Science', p. 142.
[349] Coulter, 'The Designers Leap: Boundary Jumping to Foster Interdisciplinarity between Textile Design and Science'.
[350] Lean, 'Materialising Data Experience Through Textile Thinking'.
[351] Cathryn Hall and Rebecca Earley, 'Divide, Switch, Blend: Exploring Two Hats for Industry Entrepreneurship and Academic Practice-Based Textile Design Research', *Design Journal*, 22.sup1 (2019), pp. 19–35, doi:10.1080/14606925.2019.1595848.
[352] Valentine and others, 'Design Thinking for Textiles: Let's Make It Meaningful'.

interactions with the sciences, creates unique opportunities for new design methodologies[353] including those demonstrated by my research.

This adaptive mode of working requires moving between different knowledge domains and ways of thinking and doing. It might, then, be consistent with fluid and dynamic understandings of identity, such as those expressed in Kimberlé Crenshaw's theory of intersectionality.[354] This theory describes how we present and navigate multiple and nuanced layers of identity to adapt to different social, cultural, and personal contexts. I am also reminded of Erving Goffman's 'performed self',[355] which challenges the idea that each of us has a fixed character or 'psychological identity.' Instead, Goffman argues that we present ourselves through various roles (akin to performances), and these are determined by the situations we find ourselves in. Notably, these roles require us to adapt and change depending on who we are interacting with.

Interestingly, my experience diverges from these ideas in, at least, one key aspect: The identity shift required by the transition to smart textile design is not elective in, but demanded by, the field. Goffman describes roles that one can choose to alternate between. However, the roles and learning modes I adopted (not to mention the other adaptations to my practice) have unsettled me out of my pervading view. They pushed me into a new identity as a smart textiles designer, and there can be no return to my original viewpoint or identity as a traditional textile designer. This illustrates the point at which one of my findings demonstrates the inherent adaptability within textile design. A fluid mindset has enabled me to take on, and move between, new roles and learning modes. I could then address new technical challenges and support topical project outcomes in the wearable smart textile domain.

At the same time, this raises the question of whether I have been too adaptable. Have I moved too much beyond my initial position and undergone a significant and irreversible change in my identity and thinking as a designer? This question highlights how there could be domains that the textile designer engages in (e.g. the smart textile design domain) where that engagement and the associated adapting practices (e.g. adopting new roles) render it impossible to return to an original position or perspective. In this sense, my idea of 'soft' has changed. Although still central to my work, we might say that its edges are a little harder, more refined and therefore palatable to scientific project partners. This reflects textile design's intertwinement with the 'hard' domains I have engaged with and the adaptations required for me to work therein. My attitude to practise also shifted, and my approach towards smart textile design and development is now more logical and perhaps realistic. The result is that there is a new gap between how I initially understood my aims and objectives and how I currently view them. This gap lies in my experiential understanding of the complexities of engaging and contributing in the wearable smart textile field. While I anticipated challenges and believed my expertise could offer broad impact, I now understand how my contributions are both shaped—and constrained—by dynamics, project requirements and contexts unique to engaging across disciplines. Interestingly, this shift has occurred solely as a result

[353] Coulter, 'The Designers Leap: Boundary Jumping to Foster Interdisciplinarity between Textile Design and Science', p. 138.
[354] Kimberle Crenshaw, 'Demarginalizing the Intersection of Race and Sex: A Black Feminist Critique of Antidiscrimination Doctrine, Feminist Theory and Antiracist Policies', *University of Chicago Legal Forum*, 1989.1 (1989), pp. 139–67.
[355] Erving Goffman, *The Presentation of Self in Everyday Life* (Doubleday Anchor books, 1959).

of the journey I have taken and the (internal and external) landscapes I have navigated while advancing towards new knowledge.

6.4.1. Bridging gaps between the sensory and the technical through sampling

Despite being required to prioritise technical requirements over sensory exploration, my sensorial sensibilities can still be found within the samples. Indeed, they are an inherent aspect of myself. Visual and tactile analysis highlights how I have infused my sensorial sensibilities throughout the practice and contributed to the domains where I worked through sampling. My recognition that the samples' sensory exploration of the samples could be enhanced is tacit in nature. Due to the samples' application-contexts and their intended application as innersuits, sensory experience related to qualities like texture, handle and drape have been the most important attributes with little dedicated exploration of visual aesthetics at this time. This is despite the challenge of separating aspects of sensory experience (i.e the tactile from the visual)[356] and thus, its relevance to comfort.[357] Where this kind of exploration has occurred within the research, it was limited and primarily concerned with the tactile. For instance, I focused on softening the technology to make it more *comfortable* and *wearable*. This is exemplified by my selection of suitable yarns. Focused and intentional exploration of visual aesthetics did not really enter into the work at this stage. Visual aesthetic exploration was largely tethered to highlighting functionality (see Figure 4.8a and Figure 5.6), which resulted in a deficit of opportunities to freely employ this type of understanding in the work. Moreover, the smart textile samples I created are not obviously technological devices; they are first and foremost textile fabrics (see Figure 4.4). This illustrates the inherent value of sensory awareness even when constrained.

Engaging in the development of wearable smart textiles and exploring the textile designer's role in the field (as the one who bridges gaps between sensory and technical considerations) has been shaped by the materials' technical constraints. This is especially the case when it comes to the polymeric tubing used in the case studies and the nature and particularities of the POFs. These constraints demanded specific design decisions to preserve technical functionality (e.g. adhering to the POFs minimum bend radius and ensuring that the polymeric tubing was not punctured). These constraints limited my areas of exploration. But, they also acted as a framework within which I could explore the incremental nature of balancing soft and hard in practice and demonstrate the value of a 'soft', textile approach. Progress has been achieved through small, considered and reflective steps, such as the selection of one yarn over another or one technique over another. This illustrates how 'soft' textile-focused approaches can be repurposed and embedded into the field. These examples also support design scholar Angela Duma's description of designers as 'catalysts', bringing the 'first physical reality to ideas,'[358] and the textile designer's unconscious ability to infuse sensory appeal into their design and development (even when it feels as though there is limited scope to do so). In CS1, this came through the refined selection of cream merinos (see Figure 4.11). In CS2, it was apparent in the sporty aesthetic that began to emerge during the coverstitch process (Figure 5.7). These examples of research and practice contribute to fulfilling my aim

356 Barnett, *Textures of Memory*, p. 28.
357 Matté, Broega, and Pinto, 'When Clothing Comfort Meets Aesthetics'.
358 Angela Dumas, 'Building Totems: Metaphor - Making in Product Development', *Design Management Journal (Former Series)*, 5.1 (2010), pp. 71–82 (p. 72), doi:10.1111/j.1948-7169.1994.tb00620.x.

of developing a project in the performance space that would be enhanced and enabled by textiles that people would feel comfortable wearing and that were aesthetically pleasing.

Although the samples support my primary aim of engaging in the design and development of wearable smart textiles through interdisciplinary practice, they also reveal the complexities of doing so. My 'soft' textile design approach underpinned my contribution to the sample development, thereby transforming theoretical research into tangible textile samples and advancing the samples' comfort and wearability. That said, as already highlighted in 5.4.2, I also observed that beyond my technical making skills, the culture of practice my skills emerge from has not been of significant interest or of apparent value. This reflects the broader challenge outlined in Section 1.3 (p.19). There is a lack of understanding in scientific domains about the experiential's role in the design of textiles tailored to meet nuanced consumer demands. This results in the undervaluation of sensory contributions in favor of technical priorities.

I consider sampling to be one of the discipline's 'signature pedagogies' (Section 3.3.2., p.54). Yet, textile designers run the risk of being used as technicians when they enter projects to make scientific concepts tangible. If the role of technician is adopted, then where is the space for the textile designers to offer sensory elements or synthesise the soft and the hard? How can they go beyond merely integrating technology into textiles and move towards utilising the 'full' extent of the 'textile designer's capital[359]'? I might have addressed this by being more explicit from the outset and by highlighting what I believed I could contribute. I could have emphasised the cultural and aesthetic practices that underpin textiles and demonstrated how a 'soft', responsive and adaptive textile approach to sampling imbues these qualities, enhancing wearer desirability. This is, however, not always easy to do. What textile design brings to the sensory/aesthetic sphere is still being made explicit and scientific project contributors might have considered it 'too abstract.' Such considerations come to the fore when presenting oneself in a way that will ensure the opportunity to work on the project. They point to an evolved positioning of what is sensorial/aesthetic in innovative smart textile development. They have also been integral in shaping my perspective and experiential understanding that sensorial/aesthetic attributes are just one aspect of what is required within the smart textiles field. As Schön suggests, the result can be a softening of the 'hard'/'soft' divide's edges.[360]

6.4.2. Navigating the shift

I had to manage complexity, counteract my feeling of sacrifice in the sensory/aesthetic sphere and maintain and sustain feelings of creativity while progressing towards specific and rational project goals. To do so, I adapted my construction of 'the material explorer' and turned it inward. This concept was originally developed at the beginning of the study to describe an open and explorative approach towards understanding unfamiliar material properties. Yet, it became a supportive mechanism akin to Land's 'supportive holding structure.' Indeed, it was useful for navigating the research and the disturbances

[359] Lerpiniere, 'Value Definition in Sustainable (Textiles) Production and Consumption', p. 85.
[360] Schön, *The Reflective Practitioner*.

likely to occur in such a liminal space. Land's[361] 'liminal space' is found in crossing a threshold and constitutes a difficult and precarious state of existence owing to the uncertainty and range of encountered emotions. This notion resonates with my evolution from textile designer to smart textiles designer.

Thus, the 'material explorer' became a different type of explorer from what was initially intended. It did not only support me by providing creative license and permission to lean into an explorative mindset and tangibly explore the potential of previously unfamiliar materials. Its role within the research became equally integral in navigating pathfinding's emotional toll. This involved (a) celebrating not knowing what was coming next and (b) existing in the uncertainty amid a range of emotions, which became one of my research's defining features. The 'material explorer' approach has, in turn, relied on my tacit use of one of my 'tools at hand.'[362] This is my imaginative creativity, which has been honed and developed over the years. It demonstrates how I sustained motivation and inspiration while engaged in targeted, science-led practice.

One of the textile designers I interviewed had been involved in the FAIR-SPACE project. She made a similar observation about sustaining a creative mindset, and spoke about the necessity of '*dipping back into old work*'[363] or engaging in approaches '*that can be a bit more playful.*'[364] The practice of tapping back into old work enabled her to regain an explorative and playful mindset. This demonstrates how open-ended material exploration was valuable when it came to maintaining creative momentum in this application-led space (even if it comes from outside the current project). Previous work could serve as a prompt to feel re-inspired, *"I found that to help a lot…"*[365] It also suggests that contributions to the current work began long before the work itself. It began in prior investigations and processes that were developed elsewhere. This suggests a kind of continuity in creative practice, one that is supported by research on tacit knowledge[366] and reflective practice.[367]

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[361] J H Meyer and R Land, 'Threshold Concepts and Troublesome Knowledge 1 – Linkages to Ways of Thinking and Practising', in *Improving Student Learning – Ten Years On* (OCSLD, 2003).
[362] Lévi-Strauss, *The Savage Mind*, p. 17.
[363] Miller, 'Dataset Accompanying Thesis "An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines"', p. 42.
[364] Miller, 'Dataset Accompanying Thesis "An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines"', p. 42.
[365] Miller, 'Dataset Accompanying Thesis "An Exploration of the Opportunities and Challenges of Bringing a 'Soft' Textile Design Approach into Engagement with Practitioners from Science and Engineering Disciplines"', p. 42.
[366] Polanyi, *The Tacit Dimension*.
[367] Schön, *The Reflective Practitioner*.

Chapter 7. Conclusions

In this thesis I embarked on an exploration to engage in the design and development of wearable smart textiles through interdisciplinary practice and to explore the textile designer's role within this evolving field. Rooted in my personal journey as a textile designer, my approach is true to my background, training and comprehensive understanding of the textile domain. As outlined in the preface (p.3), my foundation in textile design – shaped by diverse educational and industry experiences spanning various disciplines and applications – has informed the way I navigated the intricacies of the research. From incremental, reflective choices, such as selecting the appropriate yarn, to broader project decisions and the underlying thought processes, a wealth of tacit, embodied and experiential textile design knowledge steered my course.

However, as outlined in Section 6.2., I encountered recurring challenges in articulating this textile design knowledge within science-led contexts. These have presented themselves in this research as I have sought to address my research aims and objectives. This is seen, for instance, in relation to my objectives of identifying textile methods and values that can enhance wearable smart textiles and critically reflecting on the opportunities and challenges for textile designers contributing to their development. Thus, while developing an understanding of how my expertise can contribute to the field, I also navigated the challenges of explicating such knowledge.

This challenge was compounded by the complexities of interdisciplinary engagement (see Section 6.2), which hampered the extent to which I was able to present what I felt I could offer. These difficulties emerged not only because intertwining this form of knowledge with the prevailing science-based smart textile design discipline introduces a subjectivity which is often critiqued by the prevailing emphasis on scientific rigour, but also because in my attempt to meet the technical aims of the research I often had to step beyond my own knowledge base. Despite these difficulties, my research ultimately expanded my horizons as a designer and demonstrated the value of textile design expertise to embed comfort, wearability and sensory appeal into wearable smart textiles.

Although I selected a primarily hands-on approach, using textile sampling, the 'signature pedagogy' of the discipline, as a key method to apply and demonstrate that which I could bring to the prevailing science-based smart textile design discipline to work within this new landscape for design and address the project objectives, I made adaptations to my practices, approaches and thinking as a designer (6.3). I took on and moved between new roles and responsibilities (6.3.1.), enhanced my proficiency with technical materials (6.3.2.), broadened my design objectives from those that are primarily in the sensory and tactile domain to include those with an application focus (6.3.3.) and extended myself further into the domains of scientific project contributors through increased interdisciplinary engagement (6.3.4). This brought about a significant and irreversible shift in my identity and approach as a designer (see Section 6.3.6.), which in turn brought about myriad conflicting emotions including a sense of loss related to the extent that I was unable to work to my strengths in the sensory sphere. Nevertheless, the outcomes developed demonstrate the unconscious ability of the textile designer to impart sensory awareness during the making process, even when it feels as though there is limited scope to do so.

The research produced three key findings: the complexities of interdisciplinary engagement and how they shaped the evolving role of the textile designer within science-led smart textile contexts; the need for a fluid approach to bridge technical and creative domains and the value of integrating tacit, experiential knowledge to enhance comfort, wearability and sensory appeal.

Uncovering these has revealed the two core aspects of interdisciplinary engagement, the work undertaken with other disciplines and the work undertaken within oneself and one's own discipline. The key insight derived from my research is my transition from a traditionally trained textile designer to a smart textiles designer, which is akin to a 'threshold concept', along with its impacts and how I have navigated it. For this, I drew on one of my 'tools at hand', my imaginative creativity to develop a metaphoric practitioner-researcher identity, the 'material explorer', which I now understand as a tacit awareness for the need of a 'supportive cognitive tool' to navigate the emotional disturbances and challenges of engaging within this domain.

Some may argue that the sensory loss that has accompanied this transition is necessary, or that it is a superficial issue in the light of the pressing global issues we are collectively facing, such as resource scarcity, climate change and health inequality; and that a textile design approach that is more grounded in functional realities that are able to support and solve these problems is where the critical and future focus of the discipline should lie. Indeed, the RCA's repositioning of the Textiles Programme in 2017 from the School of Material (alongside Fashion, Jewellery, Metal, Ceramics and Glass) to the School of Design, where it is positioned with Product Design, Innovation Design Engineering and Architecture, marked a strategic shift from a purely aesthetic context to one in which it could have relevance in addressing the immediate and alarming challenges ahead related to the uncertain future. Mobilising artists and designers towards these goals is important however; it is difficult to make definitive conclusions about textile design's role and full potential within the space while there are still challenges related to its integration into the space itself. As a result of this research, I now question whether there is a problem for 'soft' tacit textile design knowledge to integrate within science-led smart textiles research domains. Upon reflection this raises the question as to whether the issue lies in the integration of 'soft', textile design knowledge within existing smart textile research frameworks or if it is a matter of ensuring that as the smart textile design domain evolves, it embraces a kind of interdisciplinarity where the space for this rich, embodied knowledge within its design processes is carved out and recognised as crucial to the equal development of the sensory/aesthetic and functional features of smart textiles. The concerns of this research are ongoing, even as this thesis 'concluded'. A 'soft' approach is being revealed as a result of this research journey and is still incomplete, and in the process of being defined.

7.1. Contributions to knowledge

This research applies 'soft', textile design approaches (encompassing both making and thinking) to the field of wearable smart textiles, demonstrating my chosen approach as a valid mode of research. It contributes to a growing body of textile design research undertaken from the perspective of a practitioner, where making, across disciplines, has been used as the central strategy for constructing knowledge. While its specific contributions are most relevant for textile design practitioners focused on the design and development of wearable smart textiles within science-led research fields, the research outcomes are also relevant to textile designers engaging in smart materials design and development for other domains where design and science converge, such as interior design or automotive design. While they derive from my own personal experiences, it is likely that these experiences are relatable and shared by many contemporary textile designers whose practices straddle both artistic and scientific realms. I hope that through this research, other textile designers' confidence about working in these spaces can be inspired where this researcher's confidence was lacking, and that those who have worked to hone and develop a nuanced skill set that includes sensorial, cultural and technical knowledge can contribute to an understanding of the value and urgent necessity of these skills in the next stage of the technological revolution.

The contributions are also relevant for science-led researchers within these interdisciplinary contexts. These include those working within disciplines that I have engaged with throughout the course of this research, such as material scientists, electrical, electromagnetic and robotics engineers, as well as those seeking to work with textile design practitioners and researchers in this domain and those who would like to develop an understanding of textile design approaches and the methods, practices and thinking of textile designers who work across domains and the potential within the structures of multi- and interdisciplinary project team.

The contributions of this research builds on the work of textile design researchers such as Rachel Wickenden, who identified that working in the technically dominated field of e-textiles required adaptations to the conventional textile design process. My research extends this by revealing the impact that these changes have had on the identity and mindset of the textile designer. I also draw on the work of textile design theorists Pajaczkowska[368] and Igoe[369], who have sought to foreground tacit textiles expertise, by applying them to scientific domains, contributing to a deeper understanding of the practical and cognitive approaches within the discipline that had been previously lacking in design research. Textile designers like Lean[370] have also similarly drawn on this foundational research and worked to communicate their textile design thinking within novel contexts, such as multidisciplinary policy departments. However, my contributions push this further and stem from the making process itself, my analysis of what it is about what I am making that is new, and the development of my role in a multidisciplinary team in order to make within it.

Therefore, my contributions lie in positioning the textile designer within the science-led smart textiles design case studies undertaken as part of this research. This furthers textile design research and practice through making within scientific fields and in the application of soft textile design knowledge and approaches to the wearable smart textile domain. These contributions are distinct and original, relating to practice, approach, and methodology. Therefore, this research advances knowledge and

368 Pajaczkowska, 'Making Known: Psychoanalysis and the Nine Types of Textile Thinking'.
369 Igoe, 'In Textasis: Matrixial Narratives of Textile Design'.
370 Lean, 'Materialising Data Experience Through Textile Thinking'.

understanding of the expertise found within the textile design discipline through making within scientific contexts.

The practical contributions of the research lie in identifying textile techniques employed during the sampling process towards the design and development of smart textiles base layers. Specifically, I develop textile design skills, like textile design sampling to create wearable smart textiles that incorporate polymer optical fibres for wearable sensing applications (see Chapter 4) and integrating networks of fluidic heating and cooling into knitted textiles for wearable thermoregulation (Chapter 5) respectively. Their application has advanced comfort and wearability of smart textile innovations being developed for environments addressed in this research, tangibly demonstrating the opportunities presented by the convergence of textile design and the sciences.

The contributions to approach made by this research lie in the broader identification of a significant identity shift from textile designer to smart textiles designer on account of engaging within the 'hard' science-led contexts of the study and the specific adaptations I made to my practice. Through this, I have developed a fluid and unboundaried approach to navigate the field of wearable smart textiles and support textile designers in making, learning, and contributing within science-led spaces, however they have been set up or however, imbalanced the team composition. This has involved several elements:

- A shift in perspective regarding the positioning of sensory experience in the creation of innovative smart textiles for environments with extreme conditions. This requires a recognition that sensory experience is just one aspect of what is required for developing innovative wearable smart textiles. This necessitates compromises in a way that may be unfamiliar to textile designers and a more practical and less abstract application of textile design expertise, a shift which supports a softening of the edges of the 'hard and soft' dichotomy as described by Schön.[371]
- The development of a metaphoric practitioner-researcher identity – 'the material explorer' – which emphasises the need to be open-minded and embrace the explorative aspects of moving between sensory and functional concerns as well as providing a supportive cognitive tool for navigating the field.
- The recognition of the need to adapt practices and adopt new roles beyond the traditional maker role which in turn highlights the need to remain open to the need to adjust or revise these roles as necessary to support the kind of research required in order to participate and contribute within these domains and to meet the research goals. This mindset supported the navigation of the expanding smart textiles research field and the emotions and shifts in thinking that arose as my design identity shifted through the course of the research, as well as a broadening in my understanding of where and how textile designers can engage and contribute to these domains.

Regarding methodology, my contributions lie in applying soft textile design approaches, or 'textile design thinking' within multidisciplinary research environments focused on smart textiles for extreme condition environments and developing the role of the designer within them. This fills a gap in the literature related to how textile designers work across the domains of textile design and the sciences in

[371] Schön, *The Reflective Practitioner*.

creating wearable smart textiles, the kinds of challenges that may arise and how textile designers may address them. This broadens the horizon of the smart textiles design field, by helping to address my aim of ensuring that ‘hard’ and ‘soft’ knowledge domains are understood to be of equal value in their development as they transition from niche applications to everyday uses.

In addition, I have identified some of the challenges that must be confronted to work across disciplines within science-led domains. For example, textile designers must beware of being too flexible in their approach, because it can lead to challenges in being able to play to their strengths within the sensory sphere. Therefore, another contribution lies in identifying challenges that impede successful interdisciplinary approaches within science-led smart textile research environments and proposing methods to achieving it in future work. I have brought these contributions together in the model presented in Section 6.3.7 (Figure 6.2), which integrates the systemic barriers identified in Section 6.2 with the context-specific adaptations developed in my practice, and demonstrates the role of a fluid mindset in embedding tacit, experiential knowledge within technically driven contexts.

7.2. Opportunities for future research

In line with reflective practice, I believe that my experiences and insights, when combined with theoretical perspectives from the literature, can inform future practices and interactions within these spaces. To this point, I have several suggestions for supporting the advancement of this research. These include areas that, first, could be explored further to support those following a similar path or the narrowing of the present disciplinary divide to more effectively synthesise the objective and technological fields with those concerned with the sensory dimensions of materiality in similar projects. Second, I suggest further work that could be undertaken on the practical samples themselves. The model presented in Section 6.3.7 (Figure 6.2) could act as a resource for either area, offering both a starting point for developing and refining practice-based methodologies in interdisciplinary contexts, and a means of becoming familiar with the kinds of challenges that might arise and how one might approach them so that work can begin from a more informed position.

7.2.1. Suggestions for future interactions across textile design and the sciences

In Section 6.2, I outlined some of the complexities of interdisciplinarity within the current context of the field that require a more equal balancing the aesthetic and technical aspects of smart textiles developments. This understanding emerged from analysis of the smart textiles practices presented in Chapters 4 and 5, as well as reflecting on the roles I assumed in my position as textile designer and the shifts in identity and approach I experienced during my research study. These shifts enabled me to participate as a designer within the science-led smart textiles domains I engaged in, yet required compromises on my part which I had not anticipated at the start of the research and which ultimately rerouted its trajectory: if I knew what I know now and I were to go back to the beginning of the research study, I might have started in a different place, but that is the nature of research. My key findings are related to the nuance and complexity inherent in my addressing my primary research object, to integrate ‘soft’ knowledge, practices and values into the smart textile domain, because rather than simply integrating these aspects, I had to adapt them in order to participate and contribute as a smart textiles designer within the field. This suggests that future work in this space might benefit from placing less value on project outcomes or how to effectively integrate methods, and more on how to navigate the inevitable disturbances of doing so

- This may involve:
    - Implementing interdisciplinarity as a key goal of the research and developing strategies to foster and monitor interdisciplinary progress, for example:
        - Implementing structural and organisational methods into the project structure, such as regular meetings and supervisions directly related to interdisciplinary goals and their progress, emphasising opportunities for experiential / bilateral knowledge exchange, such as workshops.
        - Developing/establishing a shared physical space which can act as a base for the duration of the project.
        - Integrating an intermediary skill-set facilitator with an understanding of both disciplines / the challenges of interdisciplinarity or the interdisciplinary 'agenda' (a mentor, a supervisor)**.**
        - Considering the academic hierarchy: even if the textile designer has experience elsewhere (i.e industry) they will need to fit into the academic hierarchy, which is more noticeable in science-led environments than at an arts university like the RCA.

    - Upfront recognition of the differing approaches of all of those involved – i.e, I might have shared more at the beginning of the case studies about what I could bring. This is in part related to textiles' ongoing explication of tacit knowledge and demonstrators of engagement and practice in novel contexts, so each project becomes something that can be shared.
    - Taking a step back from project outcomes and discussing broader themes such as motivations, expectations, what success looks like, what does 'completion' look like and what is achievable within a given timeline: it may be that it is not possible to expect too much from a short project, for instance, and ensure that this is all discussed openly.
    - Addressing disciplinary assumptions and sharing relevant related projects to demonstrate disciplinary capability.
    - Fostering an approach that is open and flexible in response to changing project needs.
    - Being prepared to come at the project from multiple different angles, i.e., different approaches to gathering material knowledge / learning modes.
    - Fostering patience, resilience and hopefulness – this may take the form of a metaphorical practitioner-researcher identity similar to my own notion of 'the material explorer'.
    - Seeking help and asking for more contact/ support throughout the process to better navigate the emotional toll of pathfinding.

Another area for future research that might be considered is how best to set up an interdisciplinary research project between textile design and the sciences so that each domain feels able to play to their strengths. Although my initial intention was to balance the aesthetic and technical aspects of the materials development, during the course of the research I moved further away from my knowledge base than originally intended. While this has enabled me to learn, create and contribute towards tangible outcomes with much potential for further research and development, I might have better considered how to hold on to the aesthetic at the outset, rather than assume it was something that I could easily implement at a later stage.

One approach towards addressing this could be for textile design researchers and practitioners to be a little bolder and focus on setting up and leading applications in government-funded interdisciplinary academic and industry projects themselves, rather than joining existing research networks that are science- led. I think that the domain explored within the research is a space that is open to a more flexible way of designing and which would allow 'soft' approaches to take the lead sometimes. Another approach toward addressing this could be to consider dividing the sampling process into clearly delineated phases to ensure that there is adequate time and space for giving attention to both aesthetic and functional components, even if the latter is considered to be of higher importance by scientific project contributors. I envisage that one such phase is a preliminary 'material exploration' stage. This stage involves focusing on a hands-on approach which precedes targeting sampling or prototyping. This is distinct from understanding materials from technical literature and enables the creation of 'exploratory prototyping' or 'playtypes',[372] where material exploration is not tethered to a fixed goal or objective, thus enabling freer approaches and fostering creativity and idea generation. This foundational familiarity phase is currently missing and overlooked in funded project timelines, which primarily focus on the outputs of interdisciplinary engagement but may not fully appreciate the initial gaps in disciplinary knowledge and understanding that need bridging before targeted sampling or prototyping begins. Further, it might be beneficial to approach these projects with varied starting points or initial priorities. This means not just considering the functional concerns but also giving weight to tactile and visual aesthetic aspects at the early stages of the project. In essence, this means holding different priorities in mind at the outset in order to strike a harmonious balance between technological and aesthetic concerns.

Future projects in fields such as healthcare or performance wear could also use the model developed in this thesis as a starting point to map likely barriers — for example, regulatory demands that restrict material choices or technical requirements that constrain design flexibility. From there, researchers can identify where practices may need to adapt and how to balance technical and experiential priorities. In this way, the model can be tested and implemented, demonstrating its usefulness as a tool for structuring future interdisciplinary work.

[372] Anne Marr and Rebecca Hoyes, 'Making Material Knowledge: Process-Led Textile Research as an Active Source for Design Innovation', *Journal of Textile Design Research and Practice*, 4.1 (2016), pp. 5–32, doi:10.1080/20511787.2016.1255447.

7.2.2. Education

Working in the smart textiles design space has expanded my horizons as a textile designer, opening up new avenues for the application of my skills. Yet, on account of the adaptations made to my practice, the processes/approaches and methods I now employ in my design, research and development processes are very different to those which I learnt during my undergraduate or graduate studies. This has potential implications for how textile design is taught and the kind of thinking that is embedded into courses. However, to ensure that textile design maintains its breadth and far-reaching appeal across art/craft and technical areas, it may be that elective modules, rather than compulsory changes, are most appropriate. As my research has shown, changes to processes and thinking styles can prove challenging to the learner, on account of the way that they can impact and transform identity and these changes must therefore be acknowledged and supported.

7.2.3. Further development of the samples

Although I do not intend to work with the samples developed during CS1 and CS2 immediately, given more time and with the right disciplinary input, these can be further developed, either for use within the specific environments with extreme conditions that they have been designed for, or they can be adapted for use within other domains. For example, the samples developed during CS1 could be further developed for applications in healthcare and sportswear, domains which could benefit from the development of smart textile base layers with integrated technological components capable of sensing vital biometrics, such as heart rate variability (HRV).[373]

Since completing the sampling process I have had time to reflect on the approach adopted, and whether my research efforts might be usefully placed elsewhere, were I to further develop these samples for the domains they have been produced for, and I have pinpointed the following areas:

- Joint development between textile design and fashion design to co-develop garment construction methods with textile sampling to enhance wearable smart textiles.
- Longer-term engagement that considers textile designers in the development of the POFs themselves, ensuring that POFs are developed according to their suitability for wearable applications.
- Refining the properties of the fabric:
    - achieving the right balance of fixative yarn without altering the samples' handfeel (CS1);
    - working on finer gauge knitted textile machines in order to produce finer knitted textile weights, resulting in a more wearable fabric, more akin to traditional base layers (CS1 & CS2).

[373] In sports, for example, monitoring HRV can provide athletes with information on how well the body is recovering from training. Garments with integrated HRV sensing are therefore useful for injury risk and rest and recovery strategies.

7.2.4. Greater focus on sustainable aspects of the materials developments:

Beyond the scope of this research, yet occupying in my mind throughout the research journey because of how I approach my work as a textile designer, is that textile designers can afford to ask more questions about where the technologies are going and how they might be used in the future, given their ability to gather intimate knowledge about the body and their inevitable environmental impact. It could even be argued that textile designers have a duty to consider these aspects, given the role the discipline has played in making fast fashion endlessly desirable through constantly evolving colour and pattern changes season after season. In addition, research has indicated that by combining fast fashion with integrated technological components the existing problematic nature of both the electronics and fashion industries will be compounded as a result of the challenges it will pose for garment recyclability and the drive for scalability. Among questions which could be further explored are: What is the role of design within these spaces? How can textile designers drive the sustainable development of materials in this field, and do textile designers need to be more critical about the enabling role they are playing in collecting intimate bodily data via technologies closer to the body?

Appendices

Appendix A: Finding My Research Focus

During the first twelve months of my doctoral study, I conducted a preliminary study which proved essential in guiding me towards my research focus and formulating my aims and objectives. I offer here a brief account of this study and its findings, exploring the role that making and analysing samples played in shaping my research focus and the subsequent trajectory of my research. This research required me to venture beyond the established parameters of textile design and to use my own skill set in contributing to new research avenues. I set out to expand our understanding beyond what has been achieved to date by conventional rational and targeted approaches and develop a research focus to guide my own work. The following discussion focuses on aspects of this preliminary study; a more detailed account of its specific aims, processes, and outcomes can be found in Miller, 'Crafting Material Innovation and Knowledge through Interdisciplinary Approaches'.[374]

The study involved hands-on engagement with previously unfamiliar smart and advanced materials that are not typically used in textile design. I selected three cutting-edge materials as the starting point for my exploration: ceramic fibres (high-temperature insulators); anti-static stainless-steel fibres (conductive materials), and carbon nanotubes (1D carbon nanomaterials), as shown in Figure A.1a–c. Each falls into one of two categories: they either demonstrate smart capabilities, such as the ability to sense, compute, and respond to data, or they are indicative of advanced materials developed, synthesised, and manufactured using systematic approaches within scientific settings. Rather than pursuing an application in wearable technology, I engaged with these materials to better understand how textile designers might work with smart textiles and advanced materials differently from those working within scientific and engineering fields.

[374] Claire Felicity Miller, 'Crafting Material Innovation and Knowledge through Interdisciplinary Approaches' in *Proceedings of the 4th Biennial Research Through Design Conference*, 2019, pp. 1–16, doi:10.6084/M9.FIGSHARE.7855916.V2.

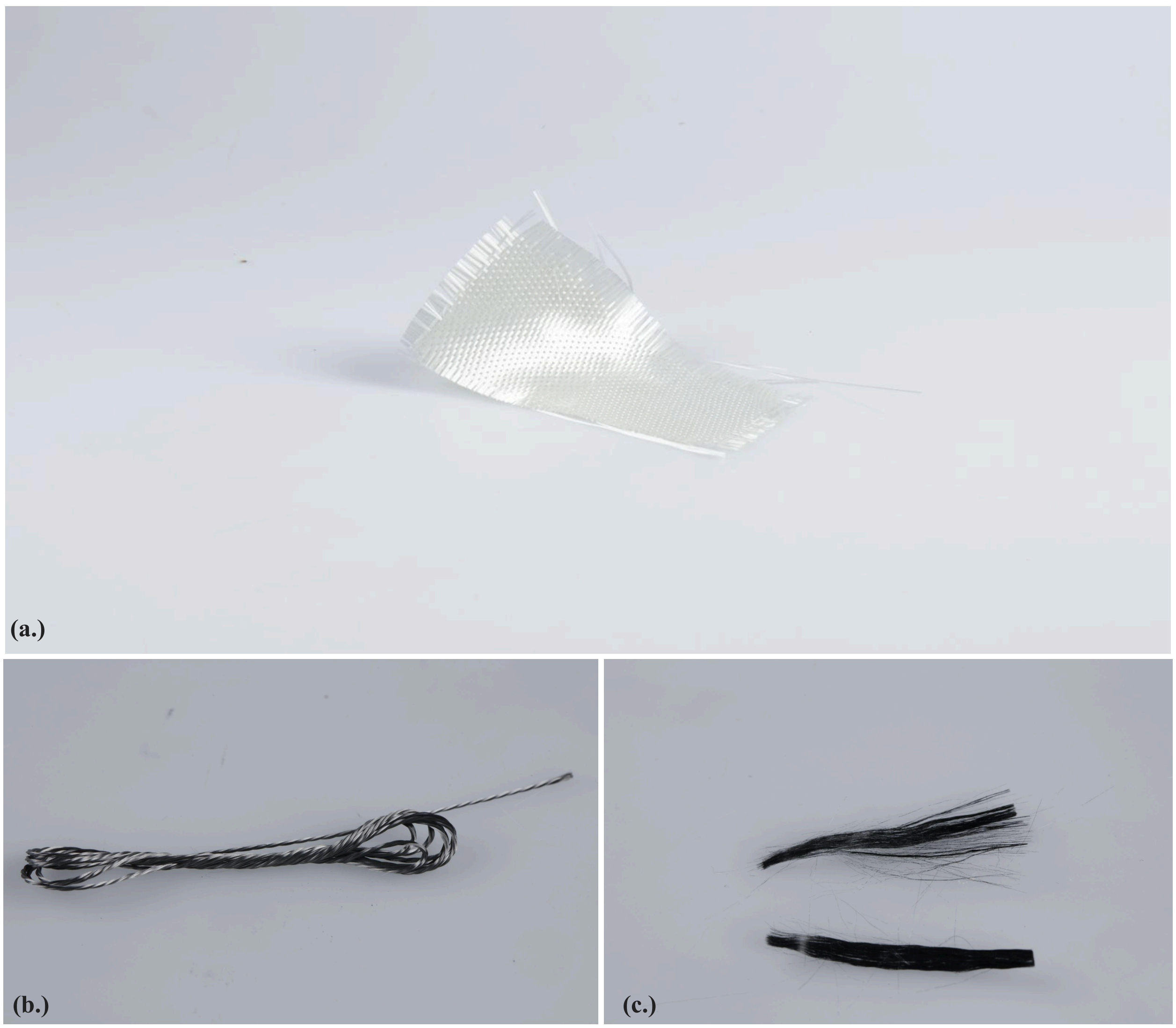

Figure A.1. a). *Ceramic fibres are high temperature insulators and widely used in extreme condition environments, such as aerospace. b.) Anti-static stainless steel fibres can be woven or knitted into electrically conductive textiles c.) The ceramic fibres which I sought to increase the capabilities of by adding conductivity as a smart capability through a carbon nanotube deposition method.*

Sampling became my primary design activity in this study, allowing me to interact with the materials and observe their behaviours in a tactile, experimental way. By exploring the physical properties of these materials through techniques such as lost-wax silver casting (Figure A.2), I developed a form of 'material knowing'[375] related to their nature and how they could be worked with. This type of knowledge is obtained through making and working directly with materials, and differs from the material knowledge we find in materials science,[376] that is useful for their quantitative analysis (Figure A.3). As a hands-on and crafts-based method with which I was already familiar, lost-wax silver casting enabled me to bring new properties and sensory expressions to the materials and gain a deeper knowledge of both what and how they are, and what they could be made to become.[377] Through these explorations, I began to see how the textile designer's experiential material knowledge might contribute to understanding and reimagining the possibilities of these materials, leading me to focus my aims and objectives (1.2.) towards exploring the untapped potential for 'soft' textile design methods to contribute to an interdisciplinary smart textile field, going beyond traditional scientific or engineering approaches. It drew my attention to the role of sampling as an embodied and reflective practice within textile research, and I developed an explicit recognition of the importance of hands-on material and interdisciplinary engagement. Indeed, it enabled me to gain practical insights into the area I wanted to focus on within smart textile design and find new opportunities for melding practice and theory to unlock new properties and sensory and aesthetic qualities.

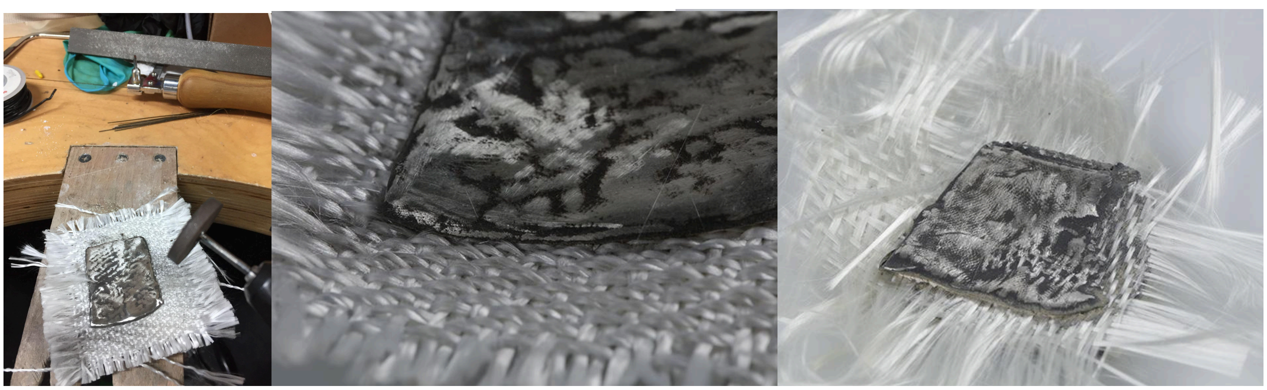

Figure A.2. *I sought to increase the functionality of woven ceramic fibres through the lost wax silver casting process. I focused on the material properties of ceramic fibres, which include an extremely high tolerance to temperature, in order to explore potential additional material properties, such as conductivity and hardness. The resulting material has both rigid and flexible elements.*

375 Tonkinwise, 'Knowing by Being-There Making: Explicating the Tacit Post-Subject in Use', p. 1.
376 Ibid., p. 5.
377 Ibid.

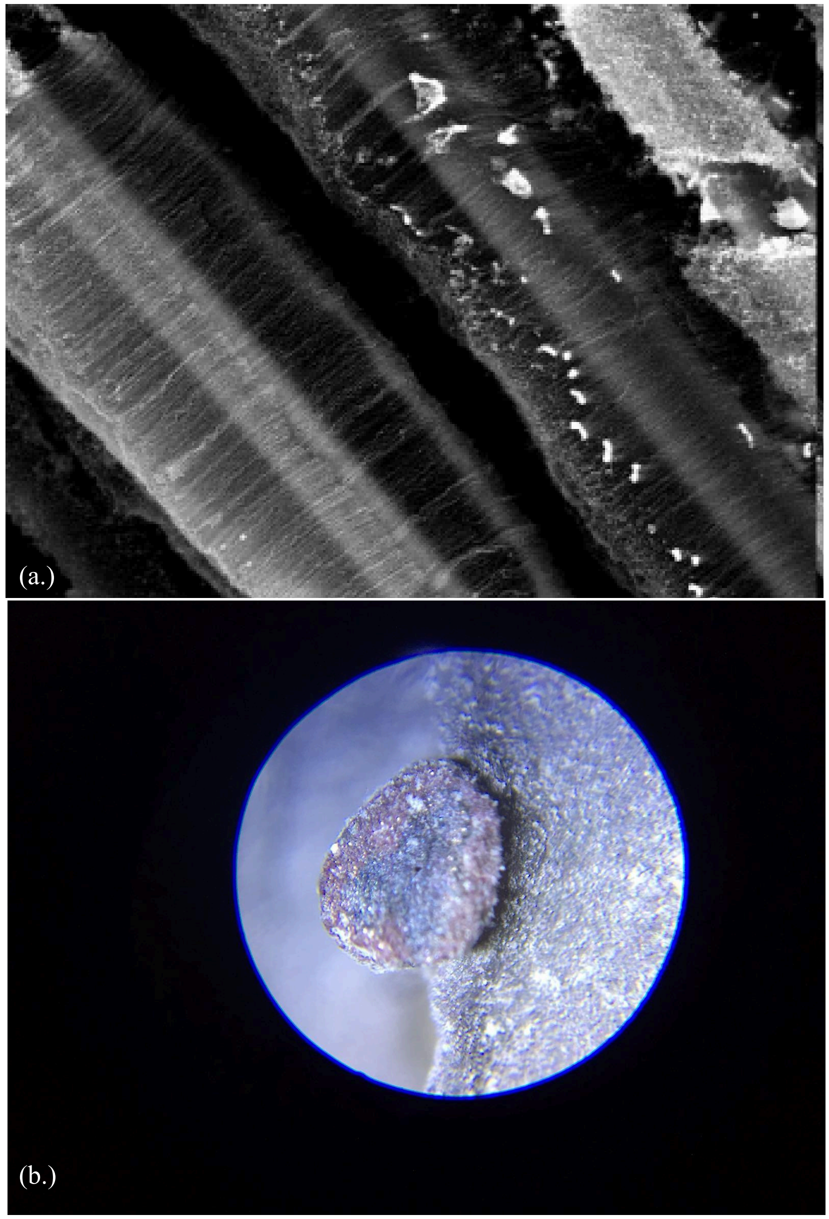

Figure A.3. *(a). Scanning electron microscope (SEM) image at 2500x magnification of successful conformal carbon nanotube growth, in line with the literature, on white ceramic fibres. Photo: Istanbul Technical University, Aerospace Research Centre (ITU ARC). (b). Magnified rigidified anti-static stainless-steel yarn encased in silver following lost-wax silver casting. Photo: Claire Felicity Miller.*

Appendix B: Optical Fibre Integration into Knitted Textiles

B.1. Introduction

A literature review and knitted textile sampling assessed existing and potential methods of integrating OFS into knitted textiles for robust on-body physiological data sensing and monitoring. The study focused on POF; however, the results could, in principle, be transferable to other OFS fibre types. The review concludes with an outline detailing the next stages of practical prototyping and research developments for Phase 2.

B.2. Key Question:

What is/are the best method(s) for integrating optical fibres into knitted textiles?

There are conflicting opinions about the ease of integrating POFs into textiles. Some suggest simple methods like stitching, laminating or glueing POFs onto ready-made fabrics or garments.[378] Rothmaier's work involved embroidering loops of POF onto an existing substrate, putting less strain on the fibre than weaving or knitting them in.[379] Examples of more sophisticated and engineered fabrics embedding POFs into the textile construction itself are more limited. This indicates the potential for impactful research requiring highly technical research alongside creative problem-solving. Some researchers have experimented with altering machinery to integrate fibres into textiles – for example, Peterson and Sandvik[380] used a flat-bed knitting machine (STOLL CMS 330 TC) to integrate POFs into knitted textiles. Their approach aligns with El-Sherif's suggestion that modifications to industrial machinery, such as adding an additional track as a feeder for OFS or electric wires, are necessary for successful integration.[381]

B.3. Material Characteristics and Fibre Properties

The properties and characteristics of POFs offer several advantages over other sensor types based on electrical conductivity. These include their flexible and lightweight nature, relative ease of integration into textiles, resistance to corrosion and fatigue and immunity to interference from electricity and magnetism.[382] Immunity to interference determined the selection of POF in this application; a vital property for robust monitoring in medical applications and hospitals, where it is necessary to avoid

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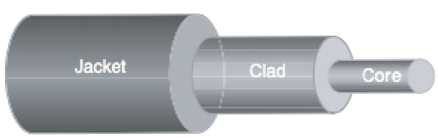
378 Wei Zeng, 'Polymer Optical Fiber for Smart Textiles', in *Handbook of Smart Textiles*, ed. by Xiaoming Tao (Springer Singapore, 2015), pp. 109–25, doi:10.1007/978-981-4451-45-1_23.
379 Markus Rothmaier and others, 'Photonic Textiles for Pulse Oximetry', *Optics Express*, 16.17 (2008), p. 12973, doi:10.1364/OE.16.012973.
380 Joel Peterson and Folke Sandvik, 'Flat Knitting of Optical Fibres', in *Autex World Textile Conference, Izmir, Turkey, 26-28 May 2009*, (Association of Universities for Textiles, 2009), pp. 1212–16
381 Mahmoud El-Sherif, 'Integration of Fibre Optic Sensors and Sensing Networks into Textile Structures', in *Wearable Electronics and Photonics*, ed. by Xiaoming Tao (CRC Press ; Woodhead, 2005), pp. 105–35.
382 Schwarz-Pfeiffer and others, 'Smarten up Garments through Knitting'; Zeng, 'Polymer Optical Fiber for Smart Textiles'; Marek Krehl, 'Polymeric Optical Fibres for Biomedical Sensing ETH Library' (ETH, 2014), doi:10.3929/ethz-a-010276893; Gorgutsa, Joanna Berzowska, and Skorobogatiy, 'Optical Fibres for Smart Photonic Textiles'.

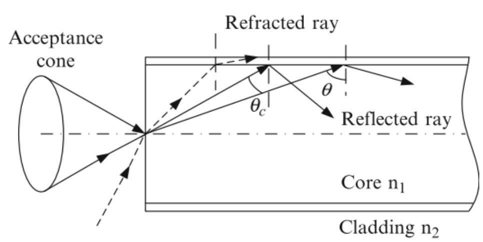
interference from the presence of strong electromagnetic fields.[383] This is also true of monitoring the health of nuclear decommissioning operators, working within environments with extreme conditions, such as Sellafield, where the thick walls of the plant could reduce the quality of a signal.

Figure B.1a shows the structure of a common POF schematic which comprises a core, cladding and jacket. This differs from the POF I worked with in this study, which was an unsheathed fibre, consisting only of the cladding and the core (Appendix H). POFs allow light to be transmitted over long distances when following a straight path; however, refraction causes luminous power to decrease when it follows a path with undulations, such as those found in looped knitted textile structures. For optimal use, they should be integrated straight, with no bends and with the 'lowest possible undulation.'[384] Figure B.1b illustrates how light enters and is guided through, refracting light within the core following the law of total reflection at the boundary of the core and the first sheath.[385]

Research into alternate polymers for POFs is ongoing. For example, Krehl[386] developed a more flexible prototype POF and Oscarsson et al.[387] noted that 'there are other polymers with good optical and textile properties that are better suited for the knitting machine'. The novelty of applications for POFs explains the lack of research and development in relation to more suitable POF for textiles.[388] Chen et al. highlighted, in 'Challenges in Knitted E-textiles', that the 'key question is whether to develop the material for better textiles integration, or to optimise the production process to suit the material'. [389]



a.)



b.)

Figure B.1. *a) Schematic diagram of a common POF, which generally comprises core, cladding and jacket layers. In: El-Sherif, Mahmoud, 'Integration of Fibre Optic Sensors and Sensing Networks into Textile Structures', in Wearable Electronics and Photonics, ed. by Xiaoming Tao (CRC Press; Woodhead, 2005), pp. 105–35, p.116). b) Schematic diagram of light guiding in a multimodal POF. In: Zeng, Wei, 'Polymer Optical Fiber for Smart Textiles', in Handbook of Smart Textiles, ed. by Xiaoming Tao (Springer Singapore, 2015), pp. 109–25, doi:10.1007/978-981-4451-45-1_23, p.111..*

383 Krehl, 'Polymeric Optical Fibres for Biomedical Sensing'.
384 Schrank and others, 'Polymer-Optical Fibre (POF) Integration into Textile Fabric Structures'.
385 Tan, Toomey, and Warburton, 'CraftTech: Hybrid Frameworks for Textile-Based Practice'.
386 Krehl, 'Polymeric Optical Fibres for Biomedical Sensing'.
387 Oscarsson and others, 'Flat Knitting of a Light Emitting Textile with Optical Fibres'.
388 Ibid.
389 Chen and others, 'Challenges in Knitted E-Textiles'.

B.4. POF for Light Emitting Textiles vs Sensors

The light-emitting qualities of POFs are often optimised through a combination of fibre and structure, as demonstrated by Taylor and Robertson[390] and Gorgutsa and others.[391] However, the ease of integrating POFs into textiles for use as wearable sensors presents different design requirements. Designing with POF for light-emitting applications may tolerate some fibre breakage for creative opportunities,[392] but this is undesirable when they are used for transmitting data as sensors. Bending POFs beyond their 'minimum bend angle' (Figure B.2) reduces the intensity of the light intensity the data detector, impacting data reliability.

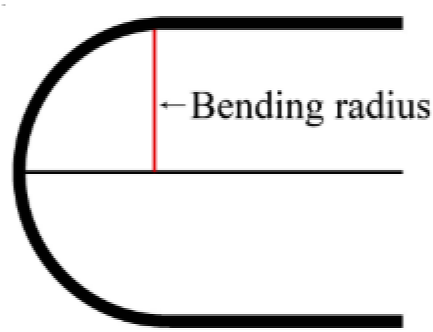


Figure B.2. *OFS bending radius. In: Oscarsson, Linda, and others, 'Flat Knitting of a Light Emitting Textile with Optical Fibres', Autex Research Journal, 9.2 (2009), pp. 61–65*

Another differentiation between POF light-emitting textiles and POF textiles for vital physiological monitoring is that the latter need secure placement at various body-locations for reliable readings. Research on integrating POFs into textile structures for use as on-body sensors is limited. Existing examples, such as one for respiratory monitoring, demonstrate functional prototypes where POFs are 'sewn onto the inside of custom-developed straps made of polyester textile, rubber straps, and a buckle'.[393] However, these samples are crude, lack refinement and show little design sensibility.[394] They are not fully integrated into the textile structure and are not scalable.

Most of the existing literature focuses on developing OFS for sensing with emphasis on the final application, rather than on effective integration. The challenge lies in 'the actual weaving, stitching and knitting of the fabrics because POF is easily broken, limiting its reliability and durability.'[395] Designers

[390] Sarah Taylor and Sara Robertson, 'Digital Lace: A Collision of Responsive Technologies', in *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program* (presented at the UbiComp '14: (The 2014 ACM Conference on Ubiquitous Computing), (ACM, 2014), pp. 93–97, doi:10.1145/2641248.2641280.
[391] Gorgutsa, Joanna Berzowska, and Skorobogatiy, 'Optical Fibres for Smart Photonic Textiles'.
[392] Tan, Toomey, and Warburton, 'CraftTech: Hybrid Frameworks for Textile-Based Practice'.
[393] Marek Krehel and others, 'An Optical Fibre-Based Sensor for Respiratory Monitoring',
[394] Zidan Gong and others, 'Wearable Fiber Optic Technology Based on Smart Textile: A Review', *Materials*, 12.20 (2019), p. 3311, doi:10.3390/ma12203311.
[395] Moo Lee, Eun Park, and Min-Sun Kim, 'Integration of Plastic Optical Fiber into Textile Structures', in *Smart Clothing: Technology and Applications*, ed. by Gilsoo Cho (CRC Press, 2009), pp. 115–34, doi:10.1201/9781420088533-c5.

with backgrounds in fashion and textile design can make significant contributions by addressing comfort, wearability and sensory appeal.

B.5. Advantages and Challenges of Designing with POFs in Knitted Textiles

Knitted textile products are favoured in wearable applications due to their properties of elasticity and comfort and the ability of their loop structure to conform to complex body shapes[396] (see Figure B.3a). These properties make knitted fabrics highly suitable for creating base layers with integrated wearable sensors: there is good sensor contact, improved accuracy in physiological monitoring and better comfort. Krehl[397] emphasised that discomfort related to smart textiles that are intended to be worn against the skin can cause distraction to a wearer, and because of this, greater consideration of comfort is required at the design stage, particularly if textile is intended for use in physically demanding environments where safety is ultimately impacted. The flexibility of knitted textiles' production and the ability to knit to shape are additional benefits, offering tailored solutions for specific applications.[398]

Although knitted textiles are a favourable choice, integrating POFs remains challenging due to their rigidity and brittleness. These fibres are prone to breaking under tensile and bending stress that are features of the looping process in knitted textiles.[399] They are therefore not well suited for the conventional knitting process, where tight bends can damage the fibre and prevent light from travelling along the full length.[400] As a result, research on POF textiles has generally focused on woven textiles, which allow for a straight integration.[401]

One method of integrating POFs into knitted textiles without damage is the 'inlay' process (Figure B.3b) where the fibre is laid straight and held in place by knitted loops.[402] Chen et al. note that 'by using inlay, a range of [optical] fiber diameters can be used, with the cited examples using POF from 0.25 to 0.75 mm'. This process is feasible, but requires optimisation for each application, POF, machine, garment shape and yarn combination.[403]

[396] Schrank and others, 'Polymer-Optical Fibre (POF) Integration into Textile Fabric Structures'.
[397] Krehl, 'Polymeric Optical Fibres for Biomedical Sensing '.
[398] Schrank and others, 'Polymer-Optical Fibre (POF) Integration into Textile Fabric Structures'.
[399] Chen and others, 'Challenges in Knitted E-Textiles', dcccxlix.
[400] Ibid.
[401] Lan Ge and others, 'Woven Light: An Investigation of Woven Photonic Textiles', in *Artificial Intelligence on Fashion and Textiles*, ed. by Wai Keung Wong (Springer International, 2018), DCCCXLIX, 53–59, doi:10.1007/978-3-319-99695-0_7.
[402] Benjamin Mohr, and others, 'Textile Integration of POF for Lighting Applications', *POF 2016 - 25th International Conference on Plastic Optical Fibres, Conference Proceedings*, *Aston University, Birmingham, 13-15 September 2016* (Aston University, 2016), pp. 118–22
[403] Chen and others, 'Challenges in Knitted E-Textiles', dcccxlix.

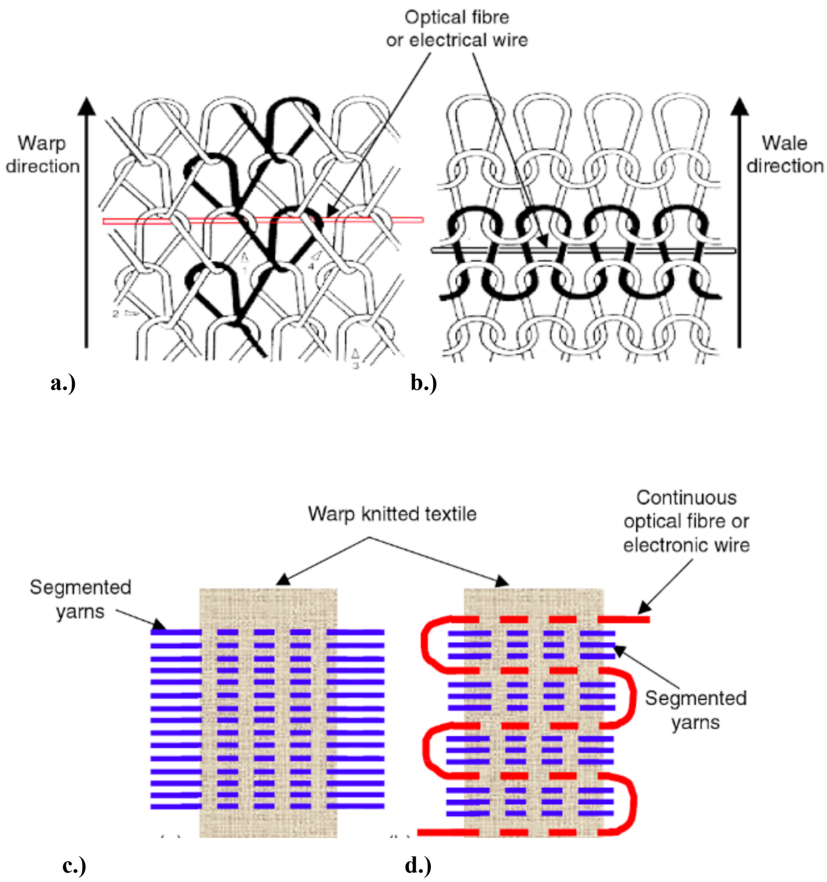


Figure B.3. *a) warp knitted textile structure with OFS inlaid into the warp. b) weft knitted textile structure with OFS inlaid into the weft. c) schematic diagrams of segmented OFS. d) Schematic diagrams of continuous OFS, taking a serpentine shape. in: El Sherif, 'Integration of Fibre Optic Sensors and Sensing Networks into Textile Structures'.*

In order to take robust biometric readings, the POF must be held securely next to the skin at specific points on the body, such as the wrist, so that they can transmit and receive light/data through the ends, which are placed next to one another. OFSs are used for tissue reflectance measurements via photoplethysmography (PPG), a non-invasive, low-cost optical technique. My knowledge in this area was gained during the workshop and influenced the design of the photonic textile samples. Figure B.4 illustrates how OFS transmit and receive light to and from the skin's surface. By illuminating the skin changes in light absorption can be measured, reflecting the changes in blood volume at each heartbeat. The elements required are a light source, such as a light-emitting diode (LED) and an optical detector used for signal measurement processing and electronics for data display.[404] As a result, the way the coupled fibres enter and leave the fibre needed to be considered within the design.

[404] Zeng, 'Polymer Optical Fiber for Smart Textiles'.

Shrank et al.[405] highlight two key ways in which this can happen. They are either segmented (see Figure B.3c) or snaked through the fabric, looping out at either side of the fabric (Figure B.3d). When snaked through the fabric, large loops at either side of fabric allow for the minimum bending curvature of POF, meeting the criteria of the specific POF in use. However, while these configurations allow POF to be integrated into knitted textile structures, Peterson and Sandvik[406] report that even when 'monofilaments are integrated into the fabric with weft insertion breakage of the fibre occurs'. In addition, this horizontal fibre within the knitted textile structure can place some design restrictions on the fabric or the garment. Inlaying the POF horizontally 'impacts the drape of the fabric and subsequently the silhouette of the garment.'[407]

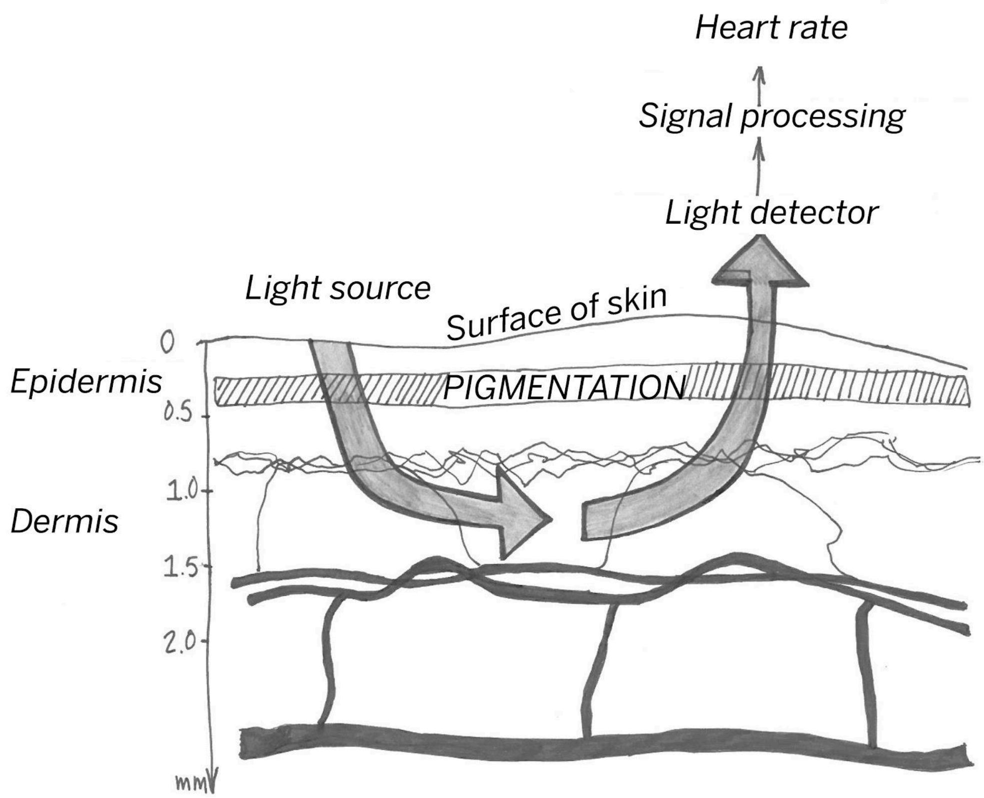
In conclusion, while there are significant challenges in integrating POFs into knitted textiles, the potential benefits in on-body physiological monitoring are considerable. For optimal use as OFS in wearable smart textiles the fibre's physical properties and the design of the textile structure and garment construction methods must all be considered simultaneously. Further research and development are needed to optimise the materials and processes for effective integration, ensuring both comfort and data reliability. The next phase of research will focus on practical prototyping and refining these integration techniques.

[405] Schrank and others, 'Polymer-Optical Fibre (POF) Integration into Textile Fabric Structures'.
[406] Peterson and Sandvik, 'Flat Knitting of Optical Fibres'.
[407] Chen and others, 'Challenges in Knitted E-Textiles', DCCCXLIX, p. 131.

TISSUE REFLECTANCE MEASUREMENTS
Photoplethysmography (PPG)

measures variation in blood volume at each heart beat

measurements taken by using fibres to deliver and receive light



Source: Prof. Steve Morgan
Footfalls and Heartbeats

Figure B.4. *Diagram showing the operating principles of gaining PPG readings using a light source and light detector (two parallel OFSs worn next to the skin), closely adapted from a presentation by Prof. Steve Morgan at the RCA Textile Design Student Workshop, 2018.*

Appendix C: Footfalls and Heartbeats and RCA Textile Design workshop

DAY	DATE & LOCATION	DETAILS
1.	Monday 15th October, 2018 FRA 304 RCA	**Footfalls and Heartbeats: Simon McMaster, Ulises Hernandez Ledezma, Prof. Steve Morgan (FHL and UoN) and RCA: Sara Robertson, Claire Miller and Sarah Taylor** · Introduction to Footfalls and Heartbeats and their current research, the project brief and the importance of novel ways to hold optical fibres securely in place for optimal readings as well as positioning on the body by Simon McMaster; · Overview of optical fibres and their sensing capabilities within health care settings and extreme environments, such as Nuclear Decommissioning. By Prof. Steve Morgan (Footfalls and Heartbeats and University of Nottingham, Photonics Group); · Sarah Taylor presented a range of artistic and functional applications of optical fibres and an overview of her weave practice working with optical fibres over the last fifteen years and her collaborative work with Dr. Sara Robertson 'Digital Lace' that creatively works with their light emitting properties, sustaining local industry and encouraging knowledge transfer related to optical fibres. · Samples and technologies were available for viewing, handling and questions; · Student participants independent research study.
2.	Tuesday 16th October 2018, MA RCA Textile Design Studios	**Claire Miller, Sara Robertson and Sarah Taylor** · Participants' team formation based on individual students' initial ideas and the themes that were emerging · Student participants' independent research study · Participating students were provided with POF optical fibres to take away and asked to begin to mock up some very early and raw initial prototypes.
3.	Wednesday 17th October 2018, MA RCA Textile Design Studios	**Footfalls and Heartbeats: Ulises Hernandez Ledezma and RCA: Claire Miller, Giulia Tomasello and Sara Robertson** · Participating student teams presentations and team debrief on project progress. Giulia Tomsello (E-textile design specialist) and Ulises Hernandez Ledezma (Photonics engineer), providing feedback; · Continued prototyping and working in teams utilising testing equipment and software being developed/optimised by Footfalls and Heartbeats) to identify optimal places on the body for OFS to gather heart rate data (for example, the wrist, finger tips or on veins and arteries).
4.	Thursday 18th October 2018, MA RCA Textile Design Studios	**Footfalls and Heartbeats: Ulises Hernandez Ledezma and RCA: Claire Miller, Sara Robertson and Giulia Tomasello** · Finalising concept and prototypes and preparing presentations in teams; · Final project team tutorials; · Final Team Presentations to Footfalls and Heartbeats & RCA Textile Design team.

Figure C.1. *CS1 workshop overview*

C.1. Project Brief

The project brief is as follows:

Footfalls and Heartbeats are leading a research project commissioned by Sellafield and UKRI to develop a new integrated system based on wearable technology that will significantly improve the productivity and comfort of nuclear operators. The integrated system comprises new 'smart basics' (suit undergarments) and an improved communication system. 'Smart basics' is an innovative approach utilising optical fibre sensors integrated within textiles to monitor both the health of the operator and the suit environment. The data provided will be used within a feedback loop to adjust air flow, temperature and humidity within the suit and provide information to the operator, buddy and supervisor about operator health and performance. The basics will provide greater comfort for the operator via the natural yarns in the textiles (thermoregulating, antimicrobial, excellent wicking properties) and the feedback will provide better air conditioning in the suit environment.

The RCA MA Textiles team are working with Footfalls and Heartbeats to integrate optical fibre sensors into textile structures for wearability. Footfalls have a range of sensor types based on both polymer and silica fibres (e.g. heart rate, oxygen saturation, respiration, humidity). However, through this workshop we will focus on a single sensor type for heart rate monitoring, keeping other applications in mind. The challenges we would like you to address should be focused on methods of:

- *Integrating the sensors into the textile structure whilst maintaining and maximising the technical functionality;*
- *Positioning on the body – is there an optimum place to position the sensors with a balance between comfort and accuracy of reading;*
- *Comfort and aesthetic – the yarn and material choice are critical for additional wearer comfort and functional benefits;*
- *Material/structural configuration – technically how can the sensors be held in the textile structure efficiently to avoid relative motion between the fibres and the skin?*

We ask you to bring your design, specialist craft and material handling skills to the challenge.

C.2. How the groups approached the brief

Group 1: Wearable Accessory
Participants: *Jinmei (May) Wang, Jieyiying (Kora) Lin, Yu (Bruce) Yang, Zieyue (Miranda) Wang*

The concept originated from initial tests aimed at identifying the best locations on the body for obtaining accurate readings. The team experimented with multiple body points and found that the area behind the ear provided consistently good readings with minimal interference or 'noise.' This led to the development of a small wearable accessory designed to be worn behind the ear.

A material sampling board was created to showcase the chosen materials, including a bendable wire that supports and secures optical fibres while allowing for customisation for individual users. The accessory incorporates craft techniques such as twisting and knotting, enabling it to be shaped or personalised to fit the wearer. The team produced a compelling final prototype with potential for further development.

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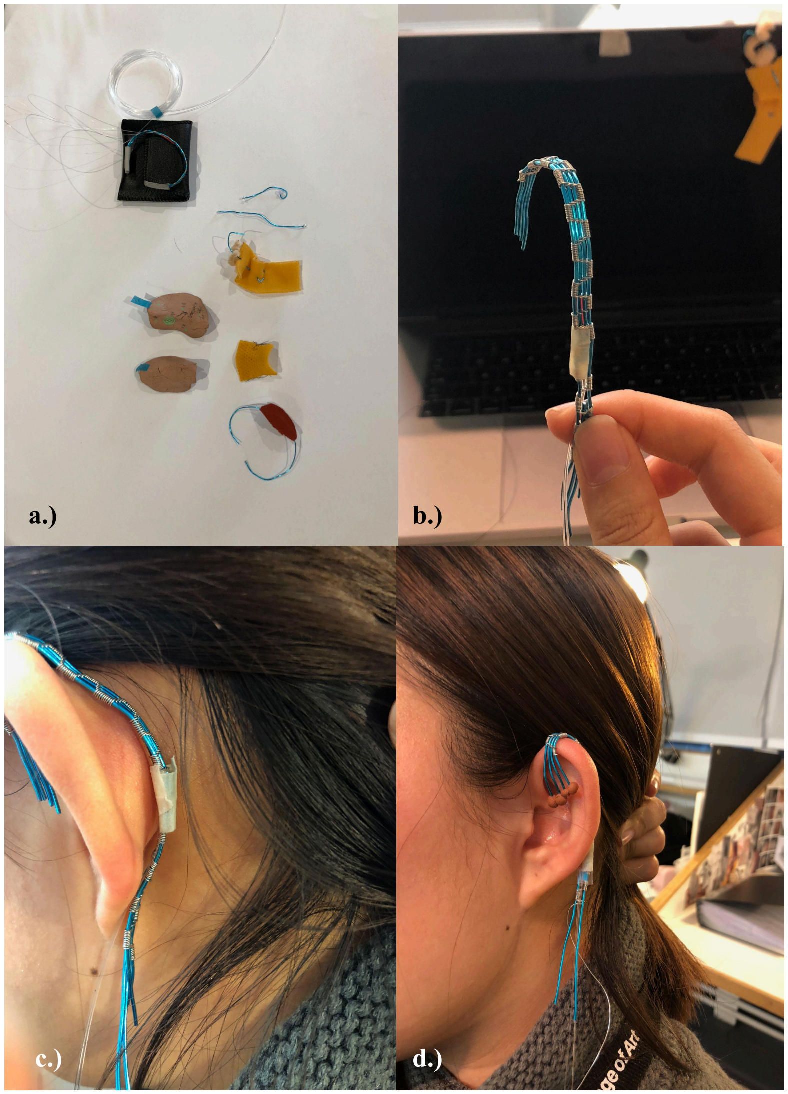


Figure C.2. *Group 1's prototype: a.) Initial sample developments b.) Final prototype c.) Prototype worn on front d.) Prototype worn on back*

Group 2: Constructed Seaming
Participants: *Alice Chamberlain, Emma Hamshare, Smriti Pasad*

The group focused on textile joining processes and design for disassembly principles, exploring concepts such as on-body strapping and wrist systems designed to be worn as part of or underneath a glove, as well as considering seams in undergarments. Various processes were tested, including hand and machine stitching, overlocking and braided structures to integrate and potentially remove optical fibres from the textile.

Elastic and nylon materials were identified as desirable for holding POFs close to the skin to capture robust readings. The choice of elastic was influenced by its common use in undergarments. Integrating POF into an elastic carrier allowed the garment to stretch with body movements, a capability not provided by the POF alone. The group's explorations in garment construction methods offered potential for further development.

Figure C.3. *Various on body strapping explorations explored by the team*

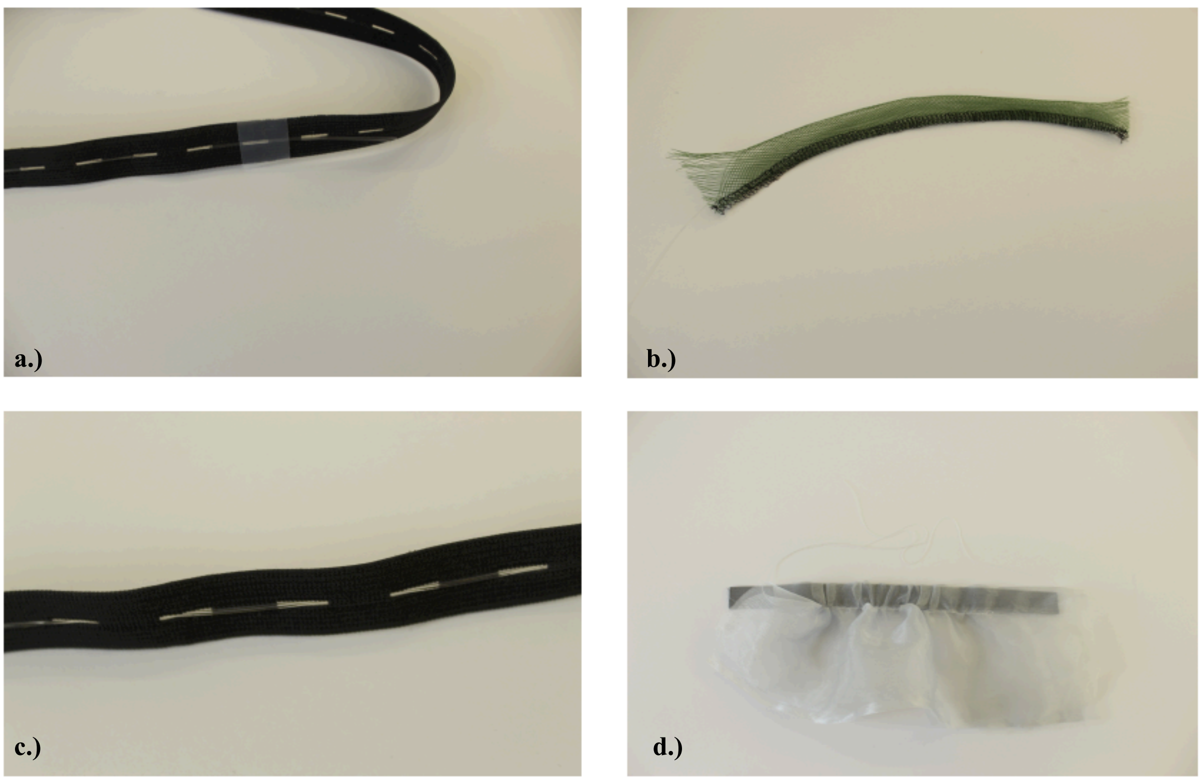


Figure C.4. *Explorations of OFS integration into elastic straps: a) Embedded in elastic strap, b) Secured by overlocking stitches, c) Close-up of (a), d) Elastic strap with OFS embedded in textile, showcasing compatibility with garment construction methods.*

Figure C.5. *OFS woven into elastic straps and a textile hem, showcasing integration with construction methods and potential body placement ideas.*

Group 3: 3D-Printed Form
Participants: *Jin Qzu (Lee) Li, Yuhan (Lemon)Zhou, Zhao Yang (Rukia) Zhang, Yin Lyu*

The group focused on using 3D-printing technologies to prototype a 'frame' designed to house and support OFS on the body. This frame, which rests over the wearer's shoulder, is constructed of circular tubes through which the OFSs are passed. The modular design allows for the frame to be detached and reconfigured into the desired shape as the individual units are printed separately. This modularity enables wearers to personalise the placement of the OFSs around the clavicle area.

The group proposed potential enhancements, such as incorporating a pressure sensor to assist with posture management and a customisable service for colour, material and finish, accessible via a mobile app.

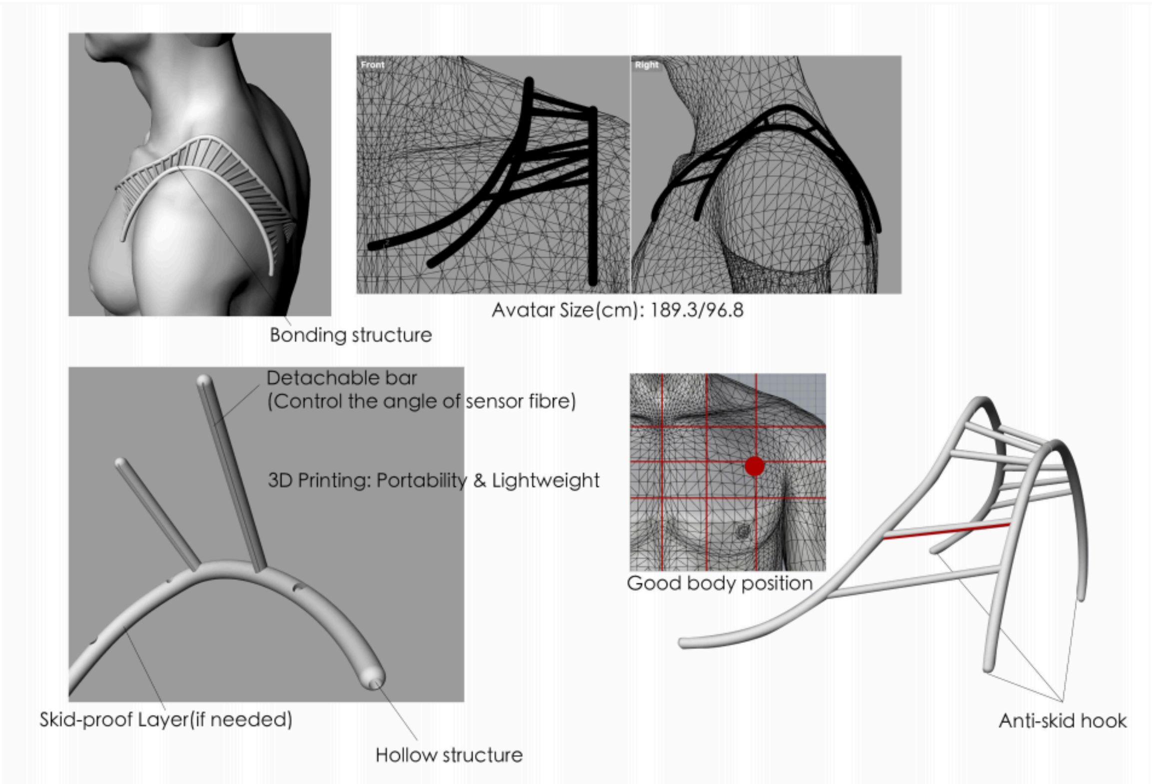


Figure C.6. *A Group 3 presentation page detailing their final design.*

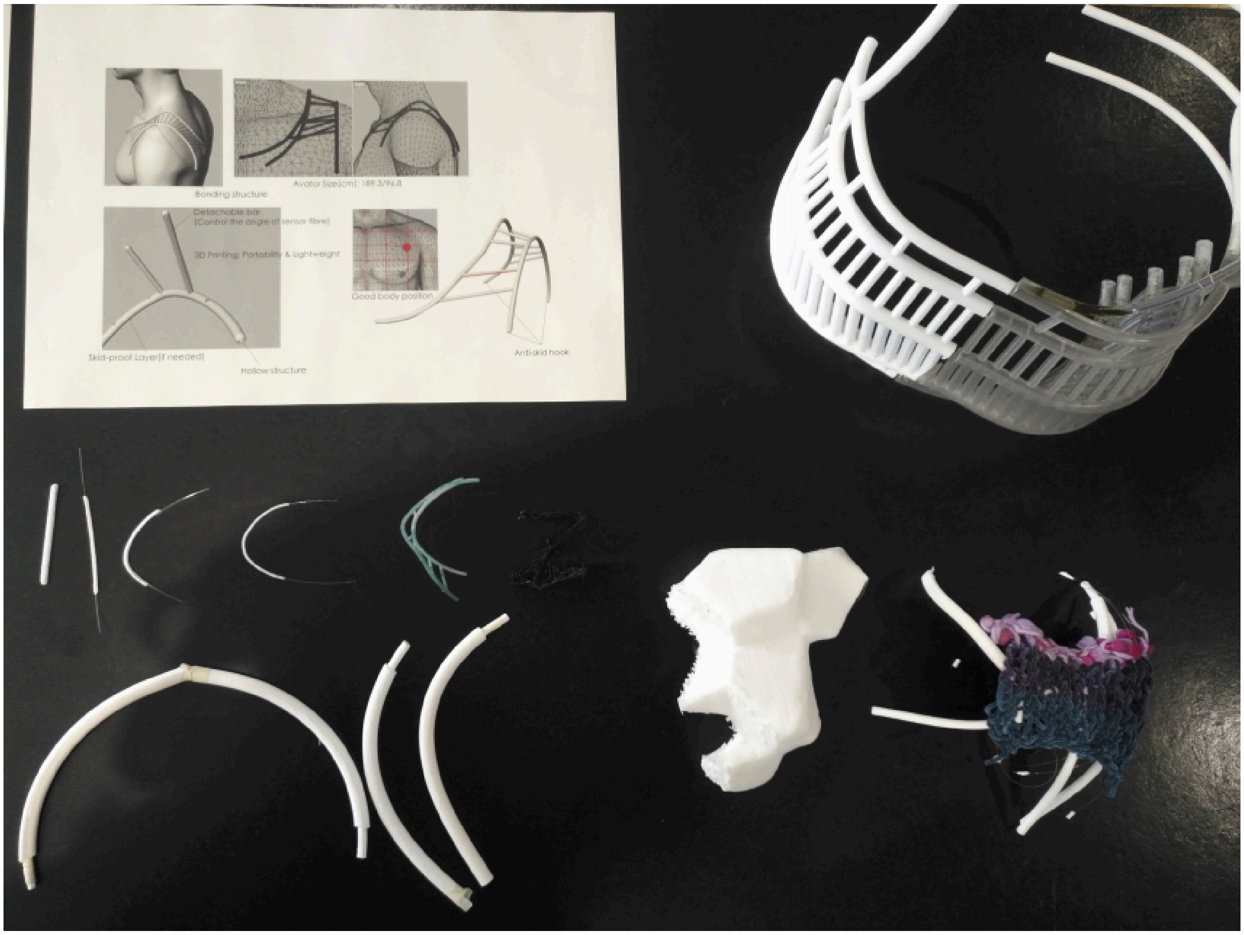


Figure C.7. *3D printed modular frame components arranged for final review*

Group 4: Responsive Materials

Participants: *Lisu Yu, Rui (Bonnie) Xu, Ying Qing (Lycee) Zhou*

Group 4 focused on integrating OFS with pH-responsive materials to create wearable accessories. They developed a concept in which professional athletes, such as dancers and gymnasts, could monitor and collect personal bodily data to enhance their performance while offering a novel aesthetic for audiences.

The group used pH-reactive inks printed on fabrics to gather additional data from sweat, complementing the HRV data collected from the OFSs. They created natural dyes from cabbage, known for its sensitivity to pH changes, which results in visible colour changes. The OFS were incorporated into a fabric strip designed as a choker, securely stitched in place.

For the textile process, they chose a velvet devoré printed fabric to reflect the luxurious and desirable materials associated with elite-level sports. The choker was positioned around the neck, a strategic point for data measurement, making it suitable for on-stage performances where visuals are crucial. The group presented samples and conducted a live demonstration of the pH changes to the fabric, showcasing the real-time data collection and visual effects.

Figure C.8. *a) PH-dyed devoré textile. b.) Final design worn during assessments c) exploring optimal reading point on neck. d) final presentation.*

Appendix D: Summary of Yarns and Fibres in CS1

NO.	YARN NAME *(from supplier)*	COLOUR	COMOSITION	DETAILS		SUPPLIER	NOTES
				Nm[1]	Dtex[2]		
1.	Medusa	White *(001)*	100% VW *(Merino)*	2/48	-	E. Miroglio SRL	Lot: 104882030
2.	Cashwool	Blue	100% VW *(Merino)*	2/30		Zegna Baruffa, Lane Borgosesia S.p.A	-
3.	Cashwool	Red	100% VW *(Merino)*	2/30		Zegna Baruffa, Lane Borgosesia S.p.A	-
4.	Baby 228	Cream (BAM5)	100% VW *(Merino)*	-	228	IAFIL S.p.A	Pt: V701931 £55/ kg
5.	Grilon	White	Nylon	-	390	EMS-Griltech	F34 T/M 100, 5001.620, 3349
6.	Grilon	White	Nylon	-	840	EMS-Griltech	F68 T/M 100 5001.481, £90/ kg
7.	FE Active	White (001250)	100% VW *(Merino)*	2/60	-	Zegna Baruffa, Lane Borgosesia S.p.A	Lot: 280340/ 000015
8.	H2 dry moisture management *(Cashwool/ teflon)*	White (001205)	100% VW *(Merino)*	2/30	-	Zegna Baruffa, Lane Borgosesia S.p.A	Lot: 585817/000015 Unito RP £50/ kg
9.	Cashwool supermelange *(Merino wool)*	Grey (421500)	100% VW *(Merino)*	2/30	-	Zegna Baruffa, Lane Borgosesia S.p.A	Lot: 306861/000018 RP £50/ kg
10.	Cashwool *(Merino wool)*	White (099054)	100% VW *(Merino)*	2/30	-	Zegna Baruffa, Lane Borgosesia S.p.A	Unito RP £50/ kg
11.	Sting overdyed	White (018266)	17% Lycra 83% Nylon	1/60	-	Bemiva	£55 /kg c.7824, 3327
12.	Arrig	Orange	90% Merino *(superfine)* 10% Polyamide	2/60	-	IGEA yarn	Lot: 51409
13.	Polymer Optical Fibre	Transparent	Unsheathed Poly Methyl Methacrylate (PMMA)	**Approx active diameter:** 0.25mm **Approx active diameter:** 0.25mm		Supplied by Universal Fibre Optics, Manufactured by ESKA Mitsubishi	Ordering code: FSPT-1-2

1. In textile yarn count, Nm (short for Number metric) is a unit of measurement that indicates the fineness of a yarn. It is calculated as the ratio of length in metres to mass in grams.
2. dtex (decitex) is a unit of yarn linear density, defined as the mass in grams of 10,000 metres of yarn. It is widely used to measure the thickness or fineness of yarns.

Figure D.1. *Overview of yarns and fibres used in CS1.*

Appendix E: Material Selection Rationale in CS1

MATERIAL COMPONENT	MATERIAL TYPE	RATIONALE	YARN NOS. *(Corresponding to those listed in Appendix D).*
Optical Fibre	Polymeric optical fibre made from Polymethyl Methacrylate (PMMA)	Sensing capability; Commercial availability; length and consistency for industrial scale use; Placeholder for UoN OAP's in-development OFS	(13)
Yarns	Merino wool	Inherent thermoregulatory properties; Handfeel; Wickability; Various colours including creams for the 'body' yarn and high contrast colours as visual indicator of intended path of POF; Compatibility with equipment.	(1, 2, 3, 4, 9, 10)
	Moisture management enhanced performance merinos	Moisture-wicking yarns to reduce perspiration-caused fibre slippage, which can reduce reliability of readings; Compatibility with equipment.	(7, 8)
	Thermoplastic speciality nylon yarns	'Supportive' yarn to prevent POF sliding, 'fix' in place through heat processing; Compatibility with equipment.	(5, 6)
	Heat-activated shrink yarn	'Supportive' yarn to prevent POF sliding by shrinking stitches around it; Compatibility with equipment.	(11)

Figure E.1. *CS1 Material selection rationale.*

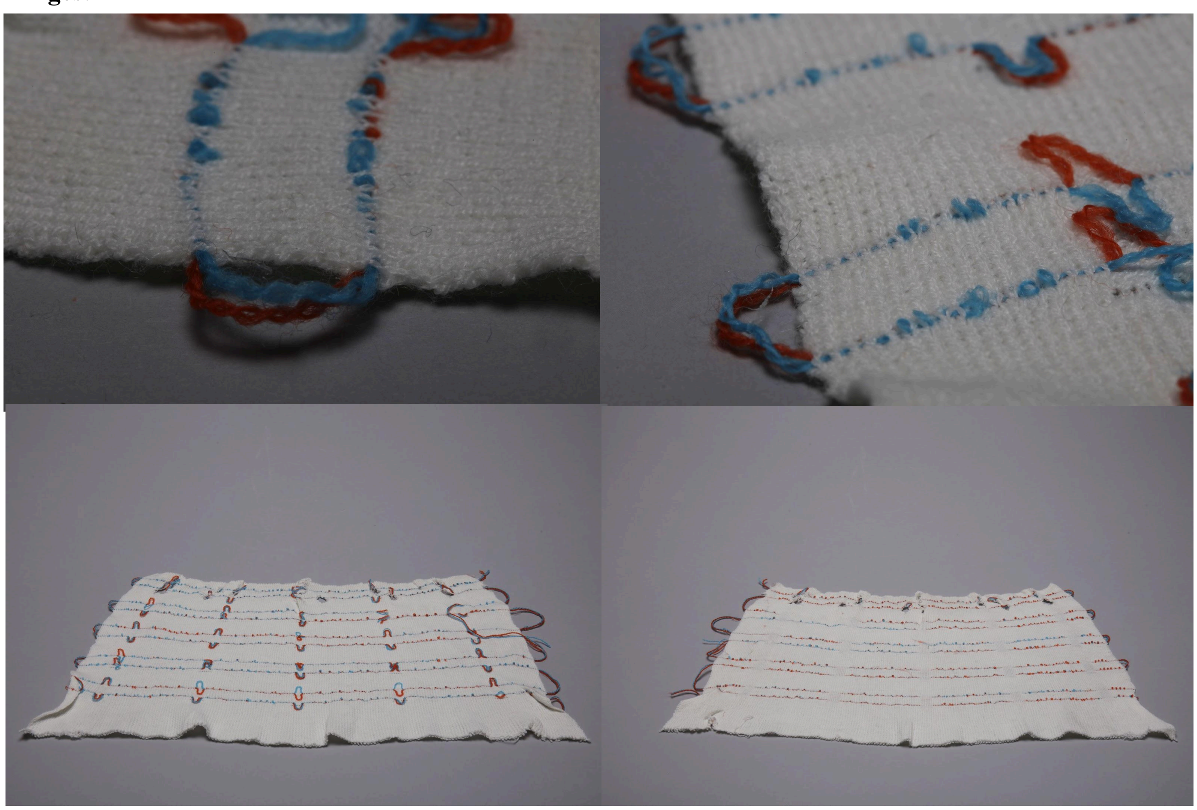
Appendix F: Summary of knitted structures and yarn combinations in CS1 samples

SAMPLE NOS.	KNITTED TEXTILE STRUCTURES	YARN NOS. *(Corresponding to those listed in Appendix D).*
1-3, 6-16	1:1 Rib Double Bed and 1:1 Rib Single Bed at reading points	1, 2, 3, 4, 5, 6, 8, 9, 10, 11 (x2), 12, 13 (x2)
4, 5	1:1 Rib Single Bed	4, 5, 13

Figure F.1. *Summary of CS1 knitted structures and yarn combinations.*

Appendix G: CS1 Material Samples

The following 16 samples were produced over two full days in November and December, 2018 the Royal College of Art, London on a Shima Seiki SRY183LP-SC industrial knitting machine, Gauge 10, using computer system and software SDS-ONE, Apex 3.3 — Knit Paint (R15).
Yarns corresponding to Appendix D

Sample#: 1
Yarns: 1, 2, 3, 5
Comments: Yarn 1 was tested as body yarn but was too fine for the knitting machine. Yarns 2 and 3 were placeholders for POF (13) integration. Yarn 5 ran parallel to test its potential for securing the POF. Fabric transitions from double to single bed exposed inlaid yarns 2 and 3, where the POF would be cut to function as light input/output, with exposed tips either facing or stacked (Table 4.1). The rib structure and inlay technique caused looping of yarns 2 and 3, risking POF damage due to minimum bend radius. Heat at 150℃ for 20 seconds was tested to examine the potential of yarn 5 as an adhesive.
Images: 

Sample#: 2

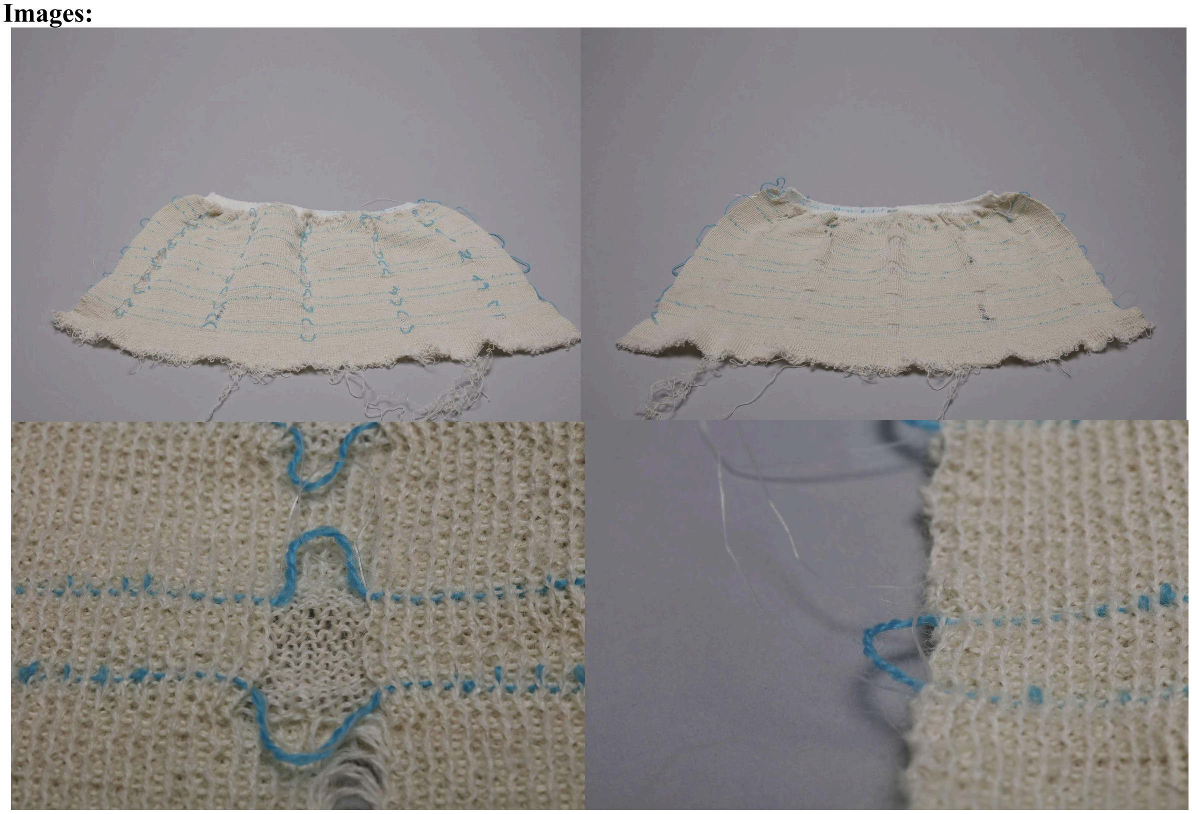
Yarns: 2, 4, 5,13x1

Comments:

Yarn 1 was replaced with 4 to address its excessive fineness. Yarn 3 was replaced with POF (13) alongside yarns 2 and 5. Half the sample was heat-pressed at 170℃ for 10 seconds to test concept viability, without temperature optimisation. In the previous sample, a single inlaid heat-fusible fiber restricted yarn movement. However, paired with POF (13), the heat-fusible fiber failed to prevent slippage.

Bottom-right image shows POF (13) extending beyond yarn (2) at the fabric edge and reading points, caused by tension release as fabric leaves the machine. This protruding POF (13) could be manually adjusted and affixed with adhesive, but the design was not optimal. Visible kinks in the POF occurred during machine insertion.

Images:



Sample#: 3

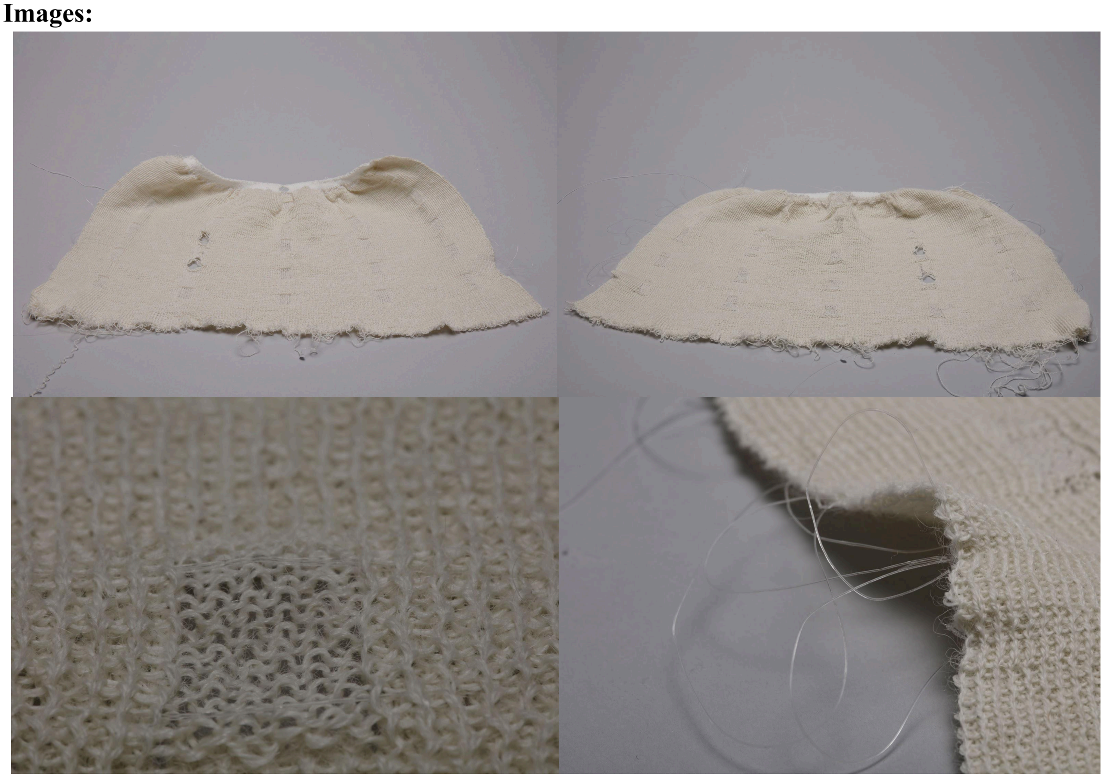
Yarns: 4, 5,13(x2)

Comments:

Yarns 2 and 3 were replaced with POFs (13). When the fabric was removed from the machine and tension released, it shrank, causing POF (13) to loop excessively at the sides and transition points from double to single bed. While the transparency of POF (13) enhanced the impression of integration, the heat-fusible yarn (5) failed to prevent sliding within the fabric. Additionally, kinks in POF (13) occurred due to it catching on the cone rim before entering the machine.

Despite these issues, manual adjustment and fixation of the fibers proved feasible, offering a potential solution for better integration and stability. The transparency of POF (13) also supports its inconspicuous integration into the textile.

Images:



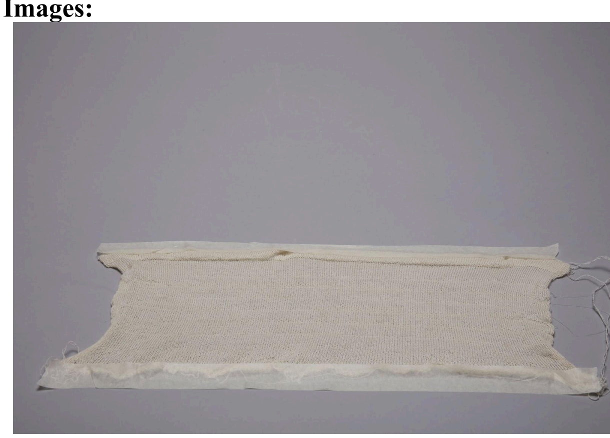
Sample#: 4
Yarns: 4, 5,13(x1)

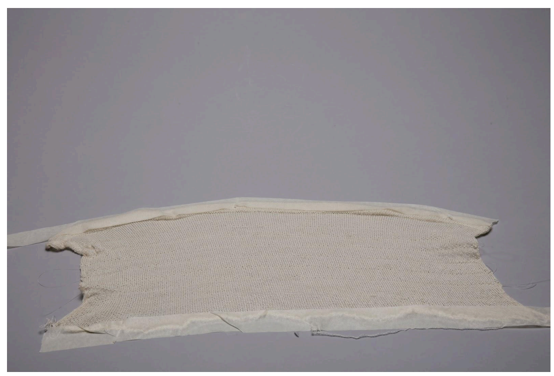
Comments:

A single-bed structure was selected to address issues of POF (13) displacement, aiming to mimic a woven fabric by securely the POF via adjacent loops and preventing looping observed in prior samples. Despite this, the POF still curled at edges, prompting a shift away from this line of sampling.

The sampling revealed that a programmed 10mm gap between the snaked rows of the POF might be inadequate to prevent fibre damage, though edge OFS showed less damage than earlier samples. This improvement likely resulted from repositioning the spool's to prevent the POF (13) catching on the rim. However, yarn (5) proved ineffective at preventing the POF (13) slippage and the body yarn (4) proved too coarse for skin contact.
(Fabric counteracts curling for photography).

Images:



Sample#: 5
Yarns: 4, 5, 13(x1)
Comments: This single-bed construction, similar to Sample 4, has fewer reading points. Heat pressing at 170 ℃ for 10 seconds (not optimised) tested if POF slippage could be prevented. However, the heat-fusible yarn (5) and POF (13) failed due to their smooth surfaces. In contrast, Samples 1-3 showed better grip as yarn (5) adhered to wool's fibrous texture. (Fabric was taped to counteract curling for photography.)
Images:  

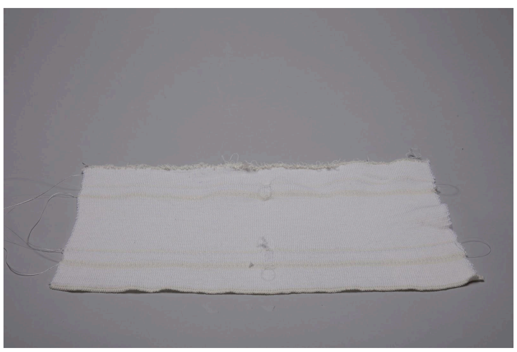
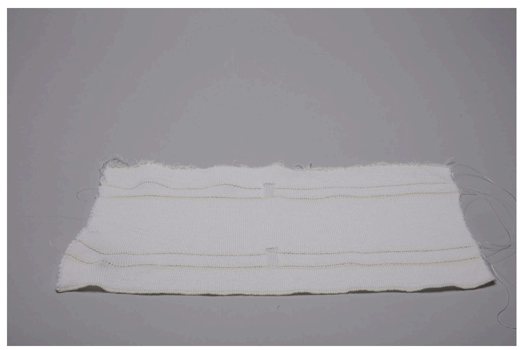
Sample#: 6

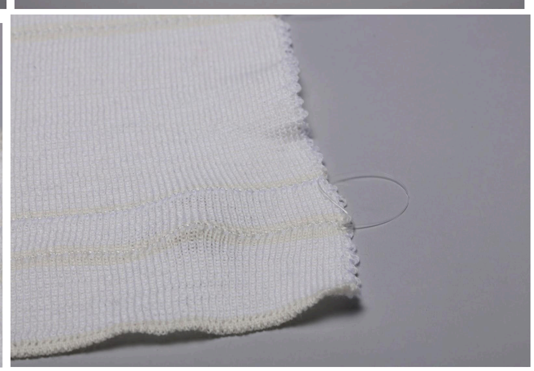
Yarns: 6, 8, 10, 11(x2), 13(x2)

Comments:

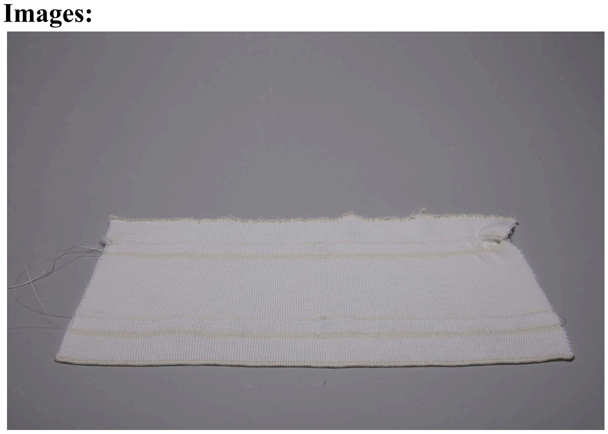
This double-bed sample used nylon/Lycra yarn (11) with moisture-wicking merino (8) and merino (10). The nylon/Lycra contracted upon steaming, tightening loops around the OFS (13), while a 'fixative' yarn (6) at reading point edges aimed to anchor the POF post-processing. High-wicking merino (8) supported moisture management to prevent sweat from compromising accuracy. Alternating merino yarns (8 & 11) reduced knit time, visible in the colour shift from cream (8) to white (10). The OFS (13) and 'fixative' yarn (6) are shown exiting the fabric. While handfeel improved, the fabric remains bulky, and the OFS (13) still slides laterally. This sample features two reading points.

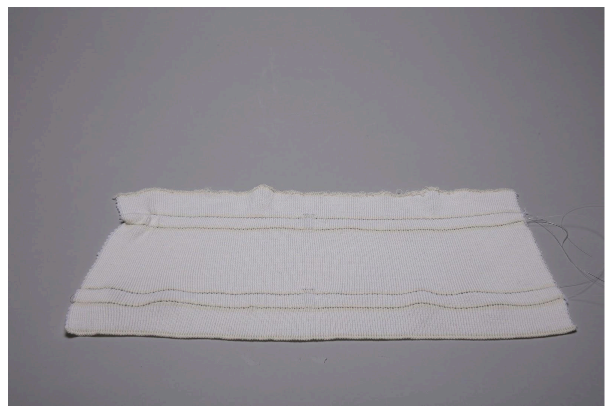
Images:

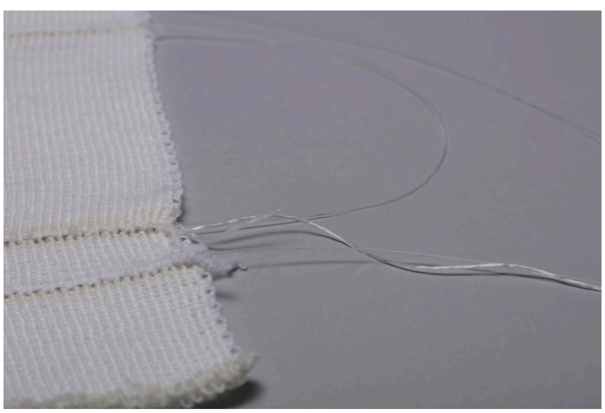





Sample#: 7
Yarns: 6, 8, 10, 11(x2) 13(x2)
Comments: This fabric was heat-processed with a steam iron held 5 cm above it for 10 seconds at 180℃. The aim was to test whether the contraction of elastic yarn (11), combined with wool (8 & 10) and heat-fusible yarn (6), could secure the POFs (13). However, the POFs (13) still slides laterally. Loops of the heat-fusible yarn (6), initially reinforced by a secondary row, lost structural integrity due to heat-induced fibre deterioration. The bottom image shows where the POFs (13) crosses the sample, highlighting the degraded heat-fusible yarn and the glossy white heat-bondable fibre (6) at the edge.
Images:







Sample#: 8

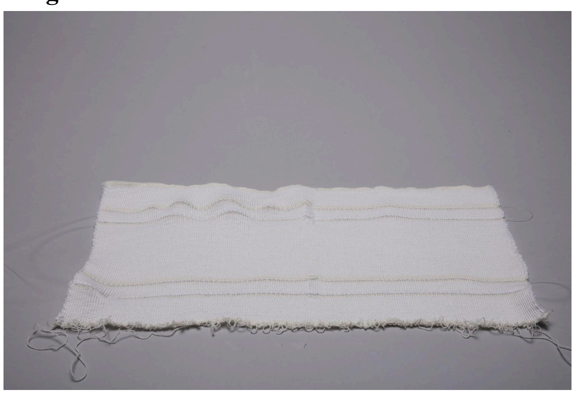
Yarns: 6, 8, 9, 10, 11(x2), 13(x2)

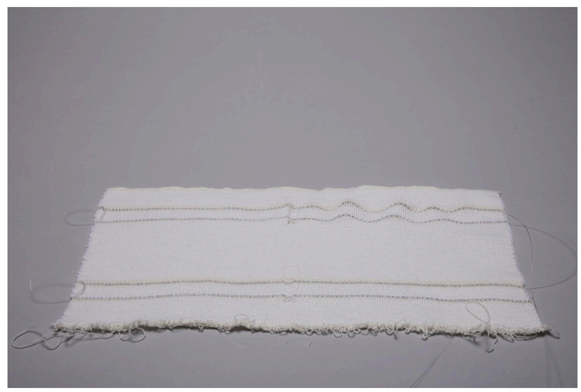
Comments:

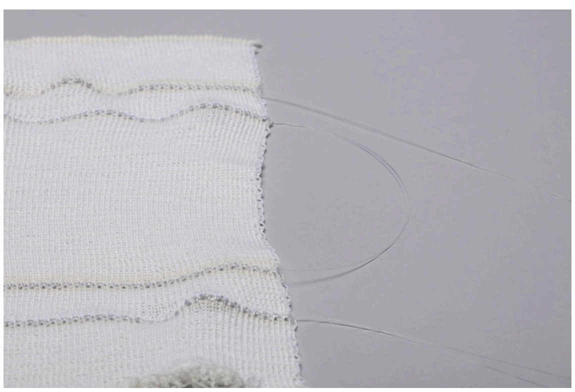
This sample aimed to address the detachment of the heat-fusible yarn (6) from stitches after heat processing, due to being coreless and running by itself. A merino yarn (9) was added alongside the heat-fusible yarn (6) to mitigate this, but the POF (13) still slides laterally.

Higher yarn density near the POF (13) causes rippling in the fabric. Final image is a close-up of the fabric face, with the POF (13) looping out at the edge.

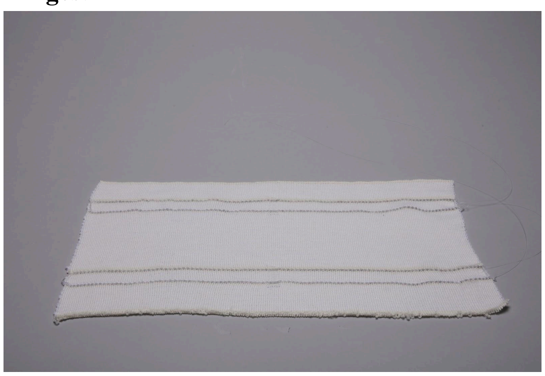
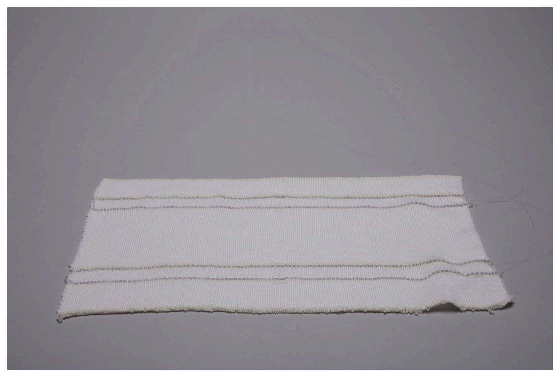
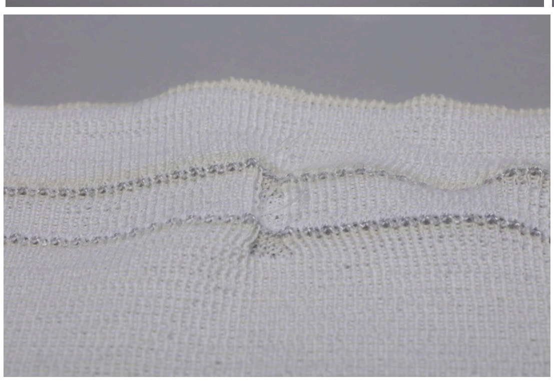
Images:







Sample#: 9
Yarns: 6, 8, 9, 10, 11(x2), 13(x2)
Comments: Similar to Sample 8, but steamed from above for 10 seconds. Post-processing, the heat-bondable yarn (6) exhibits noticeable rigidity. While the POF (13) can still move laterally, its motion is restricted. The final image shows a close-up of the transition to the single-bed construction, highlighting the POF (13) looping out at the reading point as machine tension is released.
Images:

Sample#: 10

Yarns: 6(x2), 8, 9, 10, 13(x2)

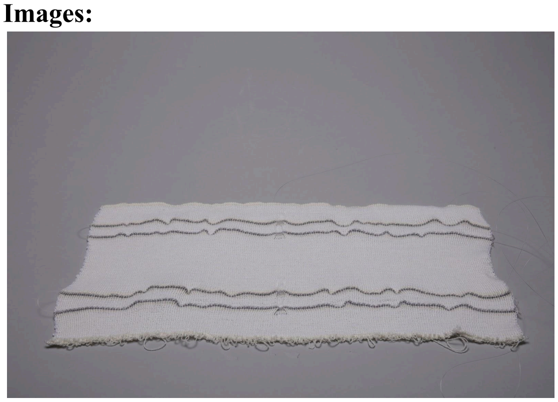
Comments:

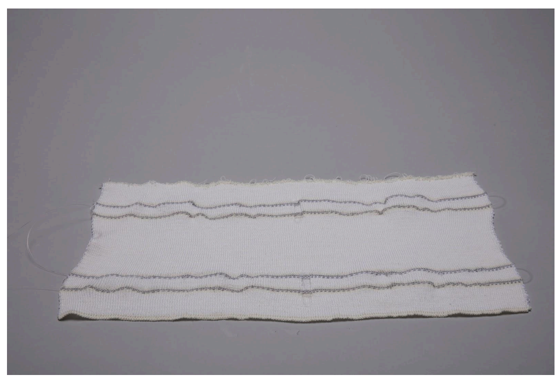
This sample, like Samples 8 and 9, replaced the elastic yarn (11) with a heat-fusible yarn (6) and wool yarn (9), encasing the POF (13) with two heat-fusible yarns (6). Gary suggested the POF (13) might kink due to contraction after detachment or steaming, possibly influenced by the elastic yarn. Removing the elastic yarn enabled heat-processing at 85℃, suitable for the heat-fusible yarn (6) and safe for the POF (13) due to its higher melting point. However, the POF (13) still kinked, indicating fibre damage.

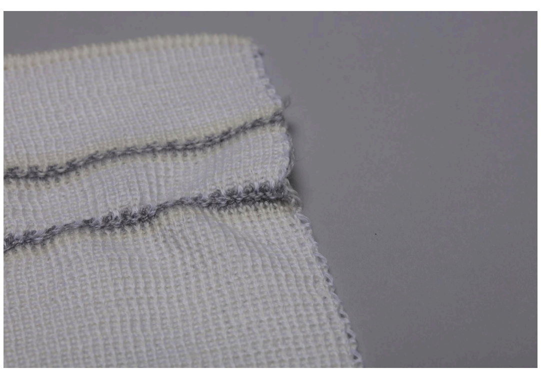
Images:

- **Top left**: Fabric front, showing yarn effects and creasing in dense areas.
- **Right**: Fabric back, with POF (13) exit point for cutting and skin contact.
- **Bottom**: Close-up of fabric edge, showing grey yarn (9) loops tightly encasing the POF (13)

Images:





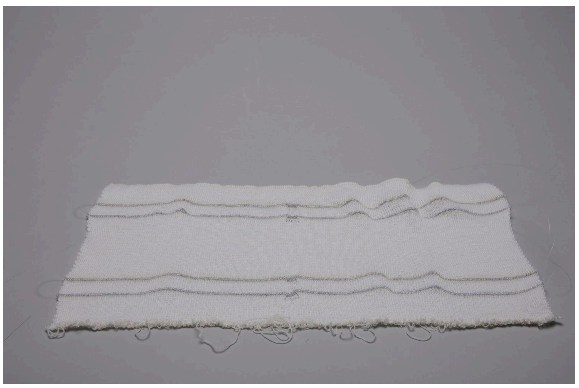
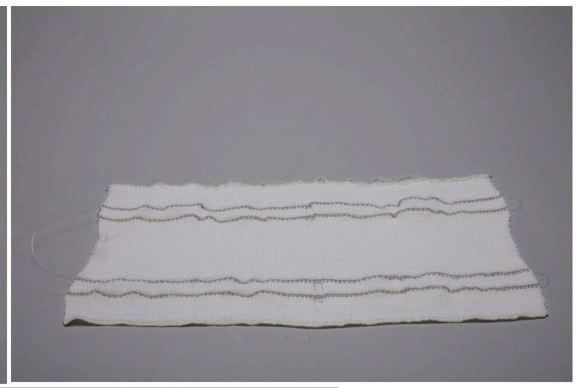
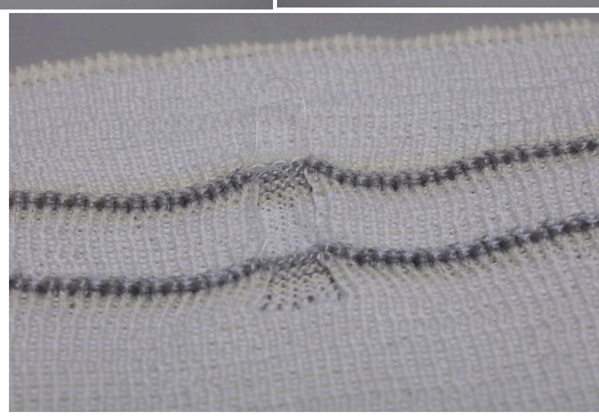


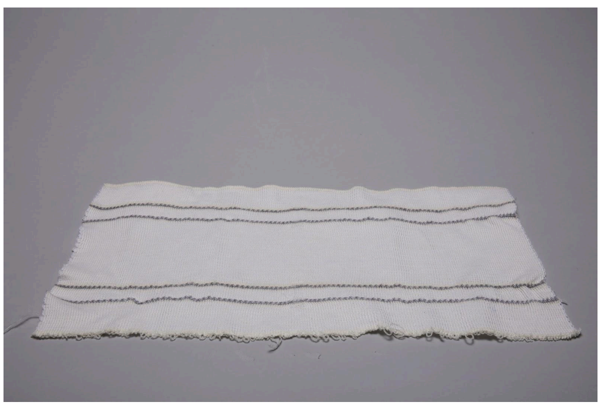
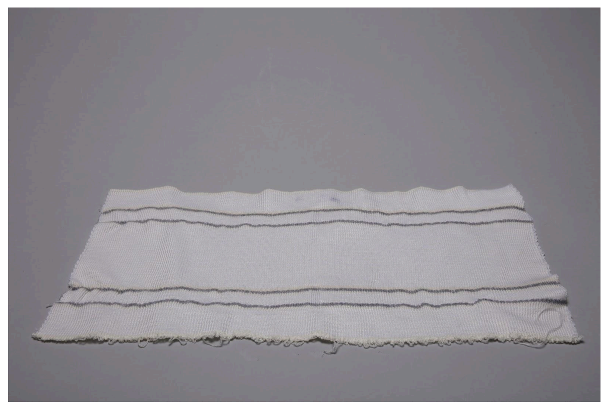
Sample#: 11

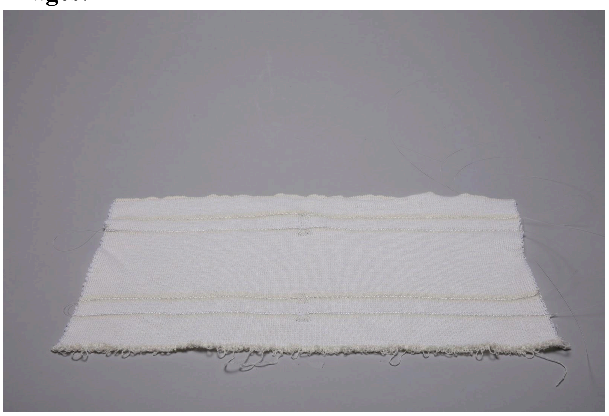
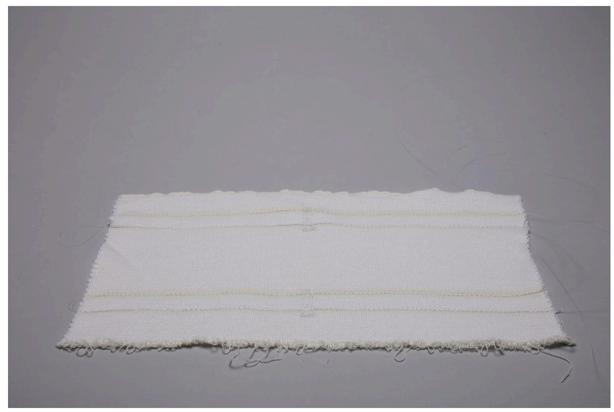
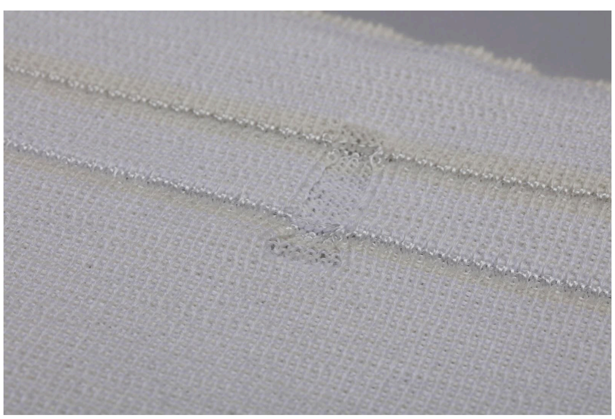
Yarns: 2, 4, 5,13x1

Comments:
This sample matches the composition of Sample 10 but uses a modified stitch structure around the inlaid POF (13) to reduce kinking. Bottom images show a close-up of a reading point where the POF (13) loops out during the double-bed to single-bed transition, with a ripple effect visible from varying yarn and fabric densities

Images:

Sample#: 12
Yarns: 6(x2), 8, 9, 10, 13(x2)
Comments: Same as Sample 11 but processed at 160℃. Although exceeding the recommended parameters for POF (13) and heat-fusible yarns (6), the heat-processing aimed to solidify the POF (13) area to limit mobility. Further optimization is needed to balance temperature, reduce POF damage, and address the heat-bondable yarn's scratchiness. While POF kinking has decreased, excessive material transfer near the POF caused uneven fabric density, rippling, and tight loops. Lateral sliding remains partially unresolved.
Images:  

Sample#: 13
Yarns: 6, 8, 10, 13(x2)
Comments: To reduce rippling from previous samples, the merino yarn (9) was removed. POF sliding improved but remains unresolved. The shiny area in the detail image (bottom left) shows unprocessed heat-fusible yarn (6) securing the OFS, while the adjacent sweat-wicking yarn (8) prevents moisture interference with data collection. The bottom right image illustrates the OFS path snaking through the fabric.
Images:    

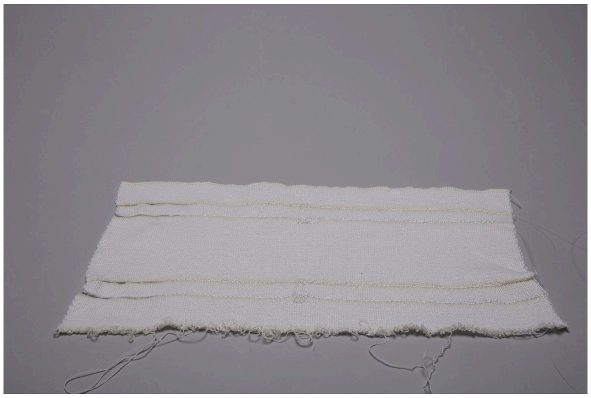
Sample#: 14

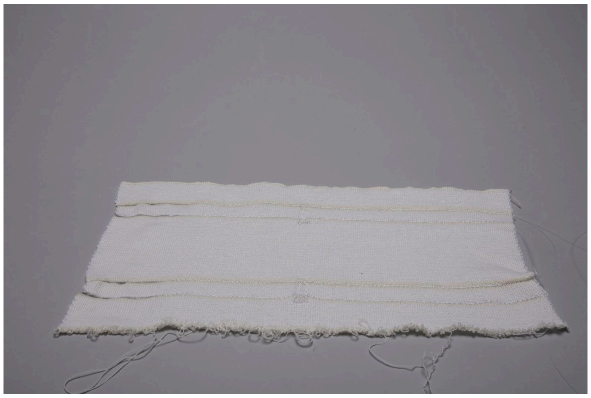
Yarns: 6, 8, 10, 13(x2)

Comments:

Same as Sample 13 but partially heat-processed to test the concept. Although the recommended maximum temperature for POF (13) and heat-bondable yarn (6) is ~85℃, a 120℃ setting was used due to heat press limitations. Despite over-processing, the sample demonstrates the concept's feasibility and potential for refinement. Using a core heat-bondable yarn could improve structural integrity post-processing.

Images:





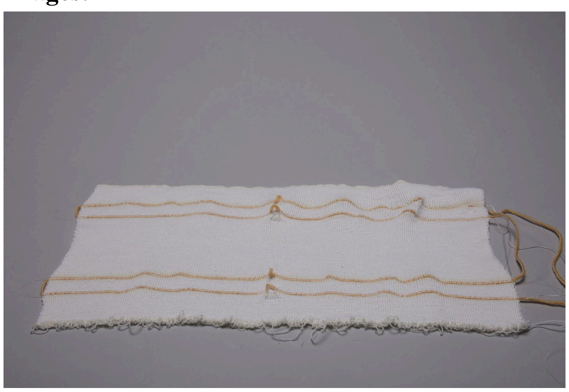
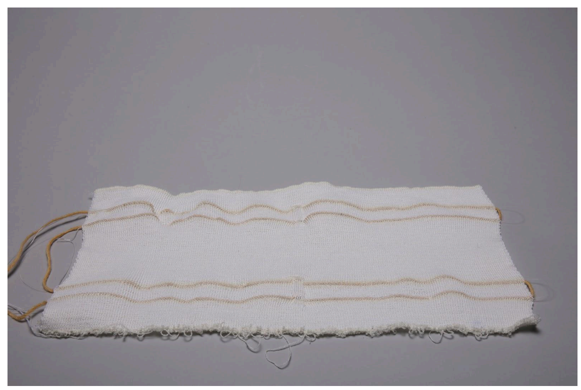
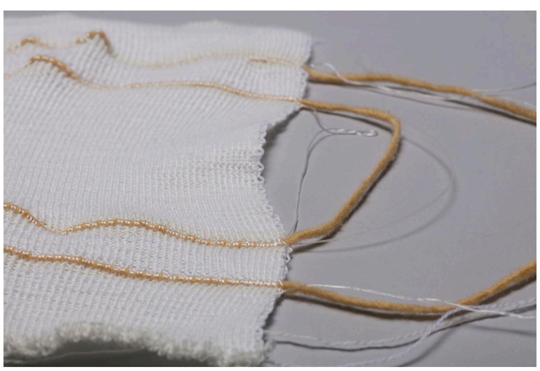
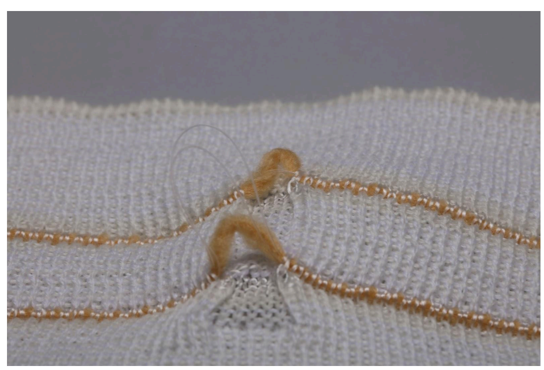
Sample#: 15

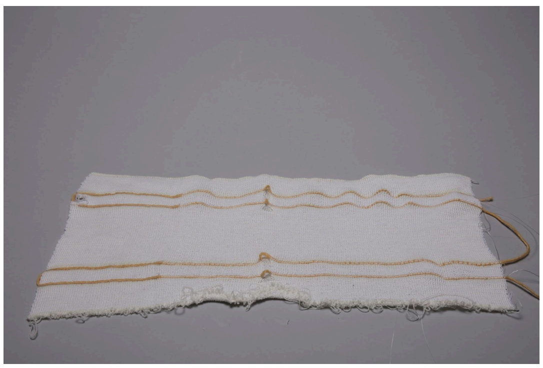
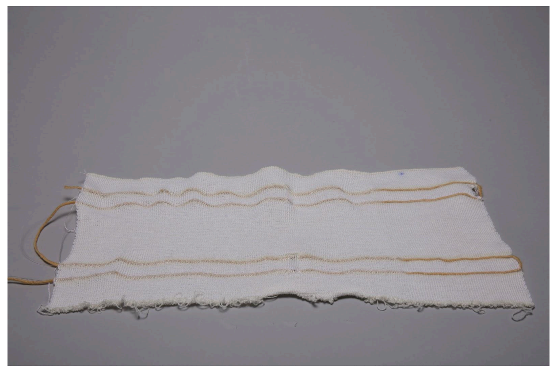
Yarns: 6, 8, 10, 12, 13(x2)

Comments:

Building on earlier samples, this concept tested running a thicker yarn (12) alongside the POF (13) to reduce lateral sliding. This resulted in minimal kinking, though ripples remain due to uneven weight distribution. Using a thicker yarn throughout the fabric could improve drape, but future development should explore finer fabrics on smaller gauge machines for base layers in hot environments. Handling revealed minimal lateral movement of the POF within the structure.

Images:

Sample#: 16
Yarns: 6, 8, 10, 12, 13(x2)
Comments: Construction and yarns same as Sample 15 but here partial heat processing has been applied to test its impact on fabric handfeel, drape and POF (13) sliding. Initial handling suggests it effectively prevented POF movement.
Images:  

Appendix H: End lit PMMA MDS

Product Specification

UFO PMMA Fibre Harness

End Lit PMMA Harness

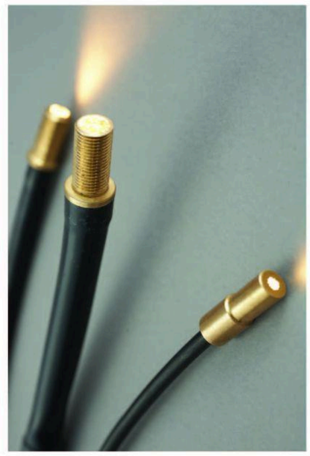
Our range of standard PMMA end lit harnesses are available in either single or multi-strand configurations. We can also make custom harnesses with larger diameter fibre if required.

Our PMMA fibre products are manufactured from Mitsubishi / ESKA raw fibre. We are an officially authorised supplier of Mitsubishi fibre products.

End lit PMMA fibre comes in two configurations - single sheathed or unsheathed strands of 0.75mm, 1mm, 1.5mm or 2mm diameter fibre, or as multiple sheathed strands of 0.75mm fibre.

Single strands of fibre give starry points of light and normally require no termination, whilst multi-stranded varieties are normally terminated with a ferrule to allow the attachment of an end fitting.

Larger diameters are available on request with soft silicone at the ends of the tails for use when articulated fittings are used in a tight space for the fibre bend radius.



	End Lit PMMA Fibre
Core Material	Polymethyl Methacrylate
Cladding Material	Fluorinated Polymer
Refractive Index	1.49
Numerical Aperture	0.5
Refractive Index Profile	Step index
Operation Temperature Range	-55°C to +70°C in low humidity; <60°C at 95% RH (attenuation change is within 10% after 1000 hours except for that due to absorbed water). Please note that fibre can become brittle at lower temperatures.
Sheathing Specifications	Outer sheathing material TP519 is a thermoplastic low-smoke halogen-free flame retardant compound with low toxic fume emission.
TP519 Toxicity Index (NES713)	1.3
TP519 Halogen Acid Gas Evolution (BS EN 50267-2-1)	<0.5%
TP519 Smoke Emission 3m Cube Test (BS 7622)	Pass

REV 7 - 140317

Universal Fibre Optics Ltd
Home Place, Coldstream, TD12 4DT, UK
Tel: +44 (0)1890 883416
www.fibreopticlighting.com

Appendix I: Summary of roles and methods, their activities and associated learning modes in CS1

ROLE IN THE PROJECT	KEY METHOD EMPLOYED	ACTIVITIES	OUTCOMES	LEARNING MODE
Desk-based researcher	Literature review	Review current advances in photonic textiles to assess the potential for integrating OFS into knitted textiles for wearability.	A literature review to support the feasibility study of the project by informing the direction taken towards textile sampling.	Reading and writing; 'know-what'.
Facilitator and co-researcher	Workshop	-Organise workshop; book workshop spaces; invite and host project partners/speakers and students; -Obtain ethics for student involvement; -Support student learning through mentoring and concept development; -Participate in the workshop as 'co-researcher'.	- Explore methods of integrating POF into textile structures; - Support expansion of the participating students' practices and knowledge related to photonic textiles—extending the impact of cutting-edge multidisciplinary work	-Hands-on; -Peer-to-peer; -Visual; Demonstrative; 'know-with' and 'know-how'.
Maker	Knitting	- Organising and booking machinery; - Organising and procuring yarn selection; - Communicating between disciplines and subject matter expertise.	- A range of knitted samples demonstrating exploration of the most promising methods of integrating OFS into knitted textile structures; - Knowledge transfer.	- Kinaesthetic; - Tacit, experiential and explicit 'know-how' and 'know-what'.

Figure I.1. *Overview of roles, methods, activities and their associated learning modes deployed in CS1.*

Appendix J: CS1 Additional Project Contextual Background

This project was developed in response to a call for proposals by the Small Business Research Initiative (SBRI), Innovate UK, and Sellafield Ltd. for a funded competition titled 'Protecting Nuclear Decommissioning Operators.' The competition sought innovative solutions to improve the productivity, safety and comfort of nuclear decommissioning operators while reducing costs. The overarching aim was summarised as developing 'an integrated solution that is safer, faster, and more affordable.'[408]

The research and practice presented in Case Study 1 (Chapter 4) forms part of this project and addresses the high-level goals of the competition outline, which were to:

- Identify the means by which nuclear decommissioning operators can achieve more, faster, while being comfortable and completely safe in their undertakings.
- Significantly improve the productivity and comfort of nuclear decommissioning operators.
- To achieve these whilst reducing cost without compromising safety.

The multidisciplinary project team proposed an innovative update to protective clothing for nuclear decommissioning operators. Protective clothing has remained largely unchanged for decades (Figure J.1). The proposed solution, termed 'smart basics', was to involve the development of body-worn textiles with integrated OFS capable of monitoring both the operator and the suit environment. This would be part of an integrated system to include an upgraded communication system being developed by one of the project partners. Key functionalities were to include data monitoring through the photonic textile, which would be part of a feedback loop, providing information relating to adjustments to temperature, humidity or air flow. This would allow an operator to be pulled out of a decommissioning environment if signs of early-onset heat stress appeared. Heat stress and the resulting rashes are common issues for operators working in decommissioning environments as a result of the bulky and impermeable personal protective equipment (PPE) that is required to be worn.

While the intended application was for nuclear decommissioning operators, the developed system, or parts of it, would be useful for many applications related to smart PPE, particularly within extreme environments.

[408] 'Competition Overview - SBRI: Protecting Nuclear Decommissioning Operators', Innovation Funding Service <https://apply-for-innovation-funding.service.gov.uk/competition/141/overview> [accessed 23 November 2024].

Figure J.1. *Nuclear decommissioning operators at Sellafield: a) in the past and b) a nuclear clean-up team today.*

The project was led by FHL, a smart textiles technology company, whose focus is on the development of textile-based sensors alongside the University of Nottingham, working on the integration of OFS developed by OAP there.[409] The broader team also included Plextex PT;[410] an electronic design consultancy, who were responsible for managing and maintaining an integrated system with an upgraded communication system providing information relating to necessary adjustments to temperature, humidity or air flow, and Romar Innovate, positioned to support the second phase of the project by field testing the ‘smart basics’ photonic textile integrated system within a suitable environment, in line with PPE regulations and requirements.[411]

The proposed range of ‘smart basics’ was selected as one of a number of projects awarded funding for the first phase of a two-phase competition. The three-month development period for selected proposals took place in early 2018. This phase required the demonstration of technical feasibility and the submission of a comprehensive plan for phase two. Despite successfully completing phase one, the project was not selected to progress to phase two. If it had advanced, phase two would have involved field testing in suitable environments to validate effectiveness and compliance with PPE standards.

[409] ‘Footfalls & Heartbeats’.

[410] ‘Plextek - Exceptional Engineering Solutions’, Plextek <https://www.plextek.com/> [accessed 26 November 2024].

[411] Romar Innovate <https://www.romarinnovatelimited.com/> [accessed 26 November 2024].

Appendix K: CS1 Ethics forms

Royal College of Art

RESEARCH & INNOVATION

Participant Project Information & Consent Form

(One signed copy of this form should be retained by the Participant and one copy by the Project Researcher)

Textiles Research Workshop

For further information
Dr. Sara Robertson:
Sara.robertson@rca.ac.uk

09 October 2018

Dear Potential Participant,

My name is Claire Miller and I am a researcher in the Textile Design department at the Royal College of Art. As part of my research, I am engaged in an interdisciplinary research project entitled 'Protecting the Nuclear Decommissioning Operator' and the project is externally sponsored by Sellafield ltd. and SBRI, Innovate UK. You are invited to take part in this research project which explores ways in which optical fibre sensors can be integrated into textile structures for wearability. The challenge of this workshop focuses on the key research aim which is to integrate newly developed optical fibre sensors into the textile structure of a garment worn by the nuclear decommissioning operator inside an outer protective. These sensors could be used to monitor the operators physiological condition within the suit and working environment.

If you consent to participate, this will involve:

— Four full days of your time (Monday 15th — Thursday 18th) in a hands-on, exploratory workshop investigating optical fibre sensor integration into textile structures.

Research Office Royal College of Art Kensington Gore London SW7 2EU
t +44 (0)20 7590 4126 f +44 (0)20 7590 4542 research@rca.ac.uk www.rca.ac.uk/research

Participation is entirely voluntary. You can withdraw at any time up to the point of publication and there will be no disadvantage if you decide not to complete the study. All information collected will be confidential. All information gathered will be stored securely and once the information has been analysed all individual information will be destroyed.

Images or quotes, which may allow you to be identified will only be used with your express permission.

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Dr. Sara Robertson at the above address.

Thank you for your interest.

I *(please print)* ……YIN LYU…… have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature……YIN LYU……

Researcher Signature……Claire Miller……

Date: ……27/10/2018……

Complaints Procedure:

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

The Research Ethics Committee
Royal College of Art

— Four full days of your time (Monday 15th — Thursday 18th) in a hands-on, exploratory workshop investigating optical fibre sensor integration into textile structures.
— The use of the results of the workshop being used for research purposes. Such as the ideas and concepts developed during the workshop. Any participation used within the published research would be credited and acknowledged.

Participation is entirely voluntary. You can withdraw at any time up to the point of publication and there will be no disadvantage if you decide not to complete the study. All information collected will be confidential. All information gathered will be stored securely and once the information has been analysed all individual information will be destroyed.

Images or quotes, which may allow you to be identified will only be used with your express permission.

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Dr. Sara Robertson at the above address.

Thank you for your interest.

I *(please print)* ....Yu Yang.................. have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature.......Yang Yu.......................................

Researcher Signature.......Claire Miller.......................................

Date: ....15/10/2018.......................................

— Four full days of your time (Monday 15th — Thursday 18th) in a hands-on, exploratory workshop investigating optical fibre sensor integration into textile structures.
— The use of the results of the workshop being used for research purposes. Such as the ideas and concepts developed during the workshop. Any participation used within the published research would be credited and acknowledged.

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Images or quotes, which may allow you to be identified will only be used with your express permission.

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Dr. Sara Robertson at the above address.

Thank you for your interest.

I *(please print)* ...Jiyue Wang... have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature......Jiyue Wang......

Researcher Signature......Claire Miller......

Date: ......17/10/2018......

— Four full days of your time (Monday 15th — Thursday 18th) in a hands-on, exploratory workshop investigating optical fibre sensor integration into textile structures.
— The use of the results of the workshop being used for research purposes. Such as the ideas and concepts developed during the workshop. Any participation used within the published research would be credited and acknowledged.

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I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature JIEYING LIN

Researcher Signature Claire Miller

Date: 15/10/2018

- Four full days of your time (Monday 15th – Thursday 18th) in a hands-on, exploratory workshop investigating optical fibre sensor integration into textile structures.
- The use of the results of the workshop being used for research purposes. Such as the ideas and concepts developed during the workshop. Any participation used within the published research would be credited and acknowledged.

Participation is entirely voluntary. You can withdraw at any time up to the point of publication and there will be no disadvantage if you decide not to complete the study. All information collected will be confidential. All information gathered will be stored securely and once the information has been analysed all individual information will be destroyed.

Images or quotes, which may allow you to be identified will only be used with your express permission.

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Dr. Sara Robertson at the above address.

Thank you for your interest.

I *(please print)* ......Yuhan...... have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature....Yuhan........

Researcher Signature....Claire Miller........

Date: ......17/10/2018........

— Four full days of your time (Monday 15th — Thursday 18th) in a hands-on, exploratory workshop investigating optical fibre sensor integration into textile structures.
— The use of the results of the workshop being used for research purposes. Such as the ideas and concepts developed during the workshop. Any participation used within the published research would be credited and acknowledged.

Participation is entirely voluntary. You can withdraw at any time up to the point of publication and there will be no disadvantage if you decide not to complete the study. All information collected will be confidential. All information gathered will be stored securely and once the information has been analysed all individual information will be destroyed.

Images or quotes, which may allow you to be identified will only be used with your express permission.

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Dr. Sara Robertson at the above address.

Thank you for your interest.

I *(please print)* Emma Hamshare... have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature.......[signature].......

Researcher Signature.... Claire Miller ....

Date: 16 · 10 · 18

— Four full days of your time (Monday 15th — Thursday 18th) in a hands-on, exploratory workshop investigating optical fibre sensor integration into textile structures.
— The use of the results of the workshop being used for research purposes. Such as the ideas and concepts developed during the workshop. Any participation used within the published research would be credited and acknowledged.

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If you have any concerns or would like to know the outcome of this project, please contact my supervisor Dr. Sara Robertson at the above address.

Thank you for your interest.

I *(please print)* SMRITI PRASAD have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature Smriti

Researcher Signature Claire Miller

Date: 15th Oct 2018

Appendix L: CS2 brief 1: Developing a polymeric fibre with integrated heating capability

L.1. Introduction

This appendix outlines the exploratory research undertaken as part of CS2 (Brief 1) at the HCRS, ICL, focusing on wearable thermoregulation challenges (Appendix S). The project aimed to develop a thermally drawn polymeric fibre with integrated heating capabilities, which could be used to construct a softer alternative to the 'flexible' wrist-worn thermoregulation and thermotherapy device developed by Kassanos et al.[412]

The design exploration was informed by the functionality of Kassanos et al. 's device, the capabilities and equipment at the HCRS, ICL and insights from literature which revealed limited prior textile applications.[413] While the proposed fibre was intended to address wearable thermoregulation, the project also sought to explore how textile design expertise might contribute to the design of wearable smart textiles through interdisciplinary engagement with practitioners from scientific disciplines. Unfortunately, due to constraints beyond my control (technical support, resources and time) the project did not progress beyond the initial stages (see Section 5.2). Here, I present the preliminary concept development, my role as a textile designer and potential next steps.

L.2. The research objectives

Through my engagement with the FAIR-SPACE project, I aimed to immerse myself in a science-led research environment to explore the contributions of 'soft' textile design expertise to interdisciplinary research on wearable smart textiles.

The proposed research was the development of a thermally drawn polymer 'fibre', with integrated heating capability, as the building block for a 'softer' textile *alternative* to the aforementioned wrist-worn thermoregulation and thermo-therapy device, developed by Kassanos et al.[414] (see Figure L.1 b&c). While flexible, on account of its move away from planar electronics that device was still rigid from a textile design perspective. I sought to understand how thermally drawn fibres could enhance both comfort and functionality.

[412] Kassanos and others, 'Towards a Flexible Wrist-Worn Thermotherapy and Thermoregulation Device'.
[413] Wei Yan and others, 'Advanced Multimaterial Electronic and Optoelectronic Fibers and Textiles', *Advanced Materials*, 31.1 (2019), pp. 1–28, doi:10.1002/adma.201802348; Ting Zhang and others, 'High-Performance, Flexible, and Ultralong Crystalline Thermoelectric Fibers', *Nano Energy*, 41 (2017), pp. 35–42, doi:10.1016/j.nanoen.2017.09.019.
[414] Kassanos and others, 'Towards a Flexible Wrist-Worn Thermotherapy and Thermoregulation Device'.

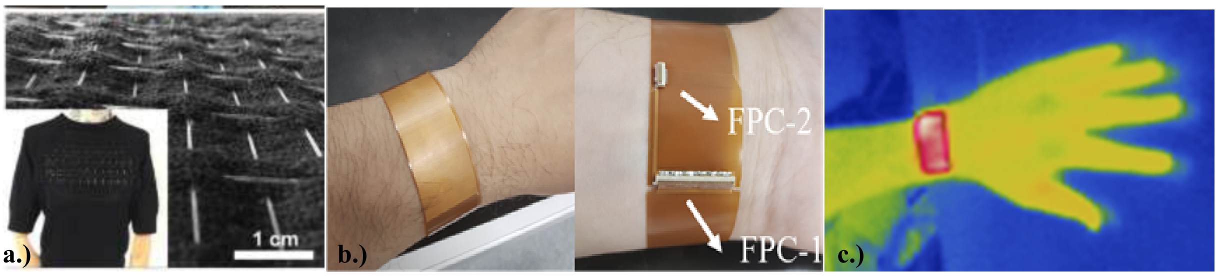

Figure L.1. *a) A thermoelectric fibre simply woven through a knitted textile. In: Ting Zhang and others, 'High-Performance, Flexible, and Ultralong Crystalline Thermoelectric Fibers',* Nano Energy, *41 (2017), pp. 35–42,* doi:10.1016/j.nanoen.2017.09.019.
Middle images show a wrist-worn thermoregulation and thermo-therapy device developed by Pangiotis Kassanos and others, 'Towards a Flexible Wrist-Worn Thermotherapy and Thermoregulation Device', Proceedings, 2019 IEEE 19th International Conference on Bioinformatics and Bioengineering, BIBE 2019 (IEEE, 2019), pp. 644–48, doi:10.1109/BIBE.2019.00121 *with two flexible printed circuits (FPC). c) Infrared camera shows the device's ability to provide localised heat.*

L.3. Design approach and sampling

L.3.1. Familiarisation with HCRL and Literature Review

To understand both the challenges faced by HCRL, ICL researchers, as well as to assess the available capabilities, in terms of expertise and equipment I engaged in consultations with scientific researchers and toured the HCRS, ICL facilities. These efforts helped me to identify where I could most effectively contribute. During the tour, I was introduced to the state-of-the-art prototype fibre thermal draw tower (Figure L.2), primarily used at the HCRS, ICL for developing prototype medical catheters. The fine polymeric tubes are designed to be inserted and steered through blood vessels during guided MRI endovascular interventions, as demonstrated by Abdelaziz and others.[415]

My proposal was informed by understanding the fibre draw tower's capabilities and its relevance for smart textile applications as well as a technical review of the literature. While there is increasing interest in exploring their potential for wearable smart textiles in areas like communications, sensing and energy harvesting,[416] there are limited examples of thermally drawn fibres in textile applications with a notable lack of textile design input.[417] This process highlighted the potential of thermally drawn fibres in wearable applications, as seen in efforts by the 'Advanced Functional Fabrics of America' network (AFFOA) to advance similar fibre developments and transform traditional textiles into sophisticated devices and systems using the thermal fibre draw process in a range of sportswear, healthcare and military applications.

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[415] Gabriel Loke and others, 'Recent Progress and Perspectives of Thermally Drawn Multimaterial Fiber Electronics', *Advanced Materials*, 32.1 (2020), p. 1904911, doi:10.1002/adma.201904911.
[416] Wei Yan and others, 'Thermally Drawn Advanced Functional Fibers: New Frontier of Flexible Electronics', *Materials Today*, 35 (2020), pp. 168–94, doi:10.1016/j.mattod.2019.11.006.
[417] Yan and others, 'Thermally Drawn Advanced Functional Fibers'; Yan and others, 'Advanced Multimaterial Electronic and Optoelectronic Fibers and Textiles'; Zhang and others, 'High-Performance, Flexible, and Ultralong Crystalline Thermoelectric Fibers'.

Figure L.2. *Fibre draw tower at HCRS, ICL. Image credit: Mohammed E.K. Abdelaziz*

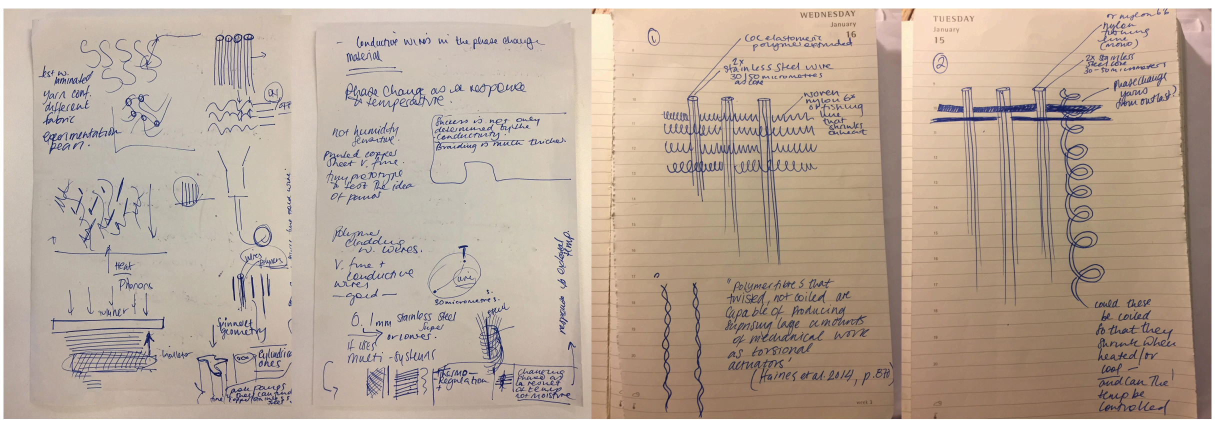


Figure L.3. *Examples of sketched idea developments in the early ideation phase.*

L.3.2 Concept Development

Inspired by Kassanos et al.'s wrist-worn device, I proposed creating a polymeric fibre with integrated heating capability that, when embedded within a constructed textile, would offer localised thermoregulation as a heat management textile system. This fibre would incorporate a core of two fine conductive metallic wires for heating to swell or shrink in response to external temperature (phase) changes, triggering a heating or cooling mechanism. I produced early sketches to visual and refine the concept, in my role as a concept developer (Figure L.3).

L.4 Material selection and challenges

For the fibre prototype, I selected two 0.03 diameter (30 micron) stainless steel wires (SS316L- round wire) from 'The Crazy Wire Company' as the conductive elements alongside a 'flexible' transparent thermoplastic elastomeric polymer (COC-E) from 'Topas' (see Appendix U). This polymer was selected on account of its previous use in thermal fibre drawing.[418]This choice was expected to limit extensive troubleshooting of the polymer during the development of a proof of concept fibre and that it would later be switched out for a polymer with the desired heat expansion properties. However, while COC-E had been previously successfully drawn using a fibre draw tower, the material presented novel challenges for those operating the fibre draw tower at HCRS, ICL. These included the determination of the correct parameters of the preform design[419] (Figure L.4) and the subsequent production of samples that did not contain any defects such as air pocket bubbles.

L.5 Sampling Results

The fibre drawing process was anticipated to be relatively straightforward, given the previous experience of HCRS, ICL researchers in integrating electrodes or wires into thermally drawn polymeric fibres to enable electrical conduction. However, the early stages of sampling brought unforeseen challenges, requiring multiple rounds of further development. For example, the first drawn fibres exhibited significant inconsistencies in diameter throughout the fibre length and were too thick for textile applications (Figure L.5a).

Despite subsequent improvements, the fibres remained overly thick, crude and 'plasticky,' making them unsuitable for fibres intended for wearing against the body (Figure L.5b). Additionally, they were too short and without sufficient elasticity, rendering them unsuitable for use within industrial knitting and weaving processes. Additionally, tension applied during industrial knitting and weaving risked causing the embedded wires to stretch or snap within the polymer. Feedback from RCA textile technicians confirmed these limitations, emphasising the need for greater elasticity and fineness. Therefore, I hand-stitched them onto knitted and woven substrates, (see Figure L.6a-c) to demonstrate their potential for textile applications.

[418] Yan and others, 'Thermally Drawn Advanced Functional Fibers'; Loke and others, 'Recent Progress and Perspectives of Thermally Drawn Multimaterial Fiber Electronics'; Chi Lu and others, 'Flexible and Stretchable Nanowire-Coated Fibers for Optoelectronic Probing of Spinal Cord Circuits', *Science Advances*, 3.3 (2017), p. e1600955, doi:10.1126/sciadv.1600955.
[419]There are several methods that can be used to fabricate a preform and while 3D printing is a more convenient process, suitability depends on the polymer choice. Since the polymer used here is provided in pellets, the more traditional process of creating a metallic mould was required, both a more time and labour intensive process. Further details related to the process of thermal drawing as well as current progress and advances can be found in the work of Yan and others. (2020).

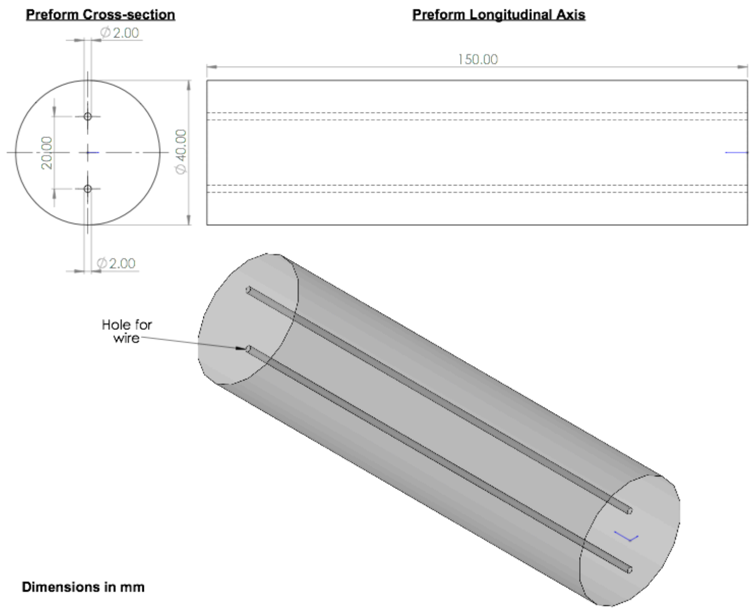


Figure L.4. *Fibre draw tower preform dimensions diagram drawn by a scientific project contributor. Image credit: Mohammed E.K. Abdelaziz. The diagram offered a visual method for communicating across multiple disciplines, particularly the technician involved in fabricating the pre-form where precise dimensions for the mould were required.*

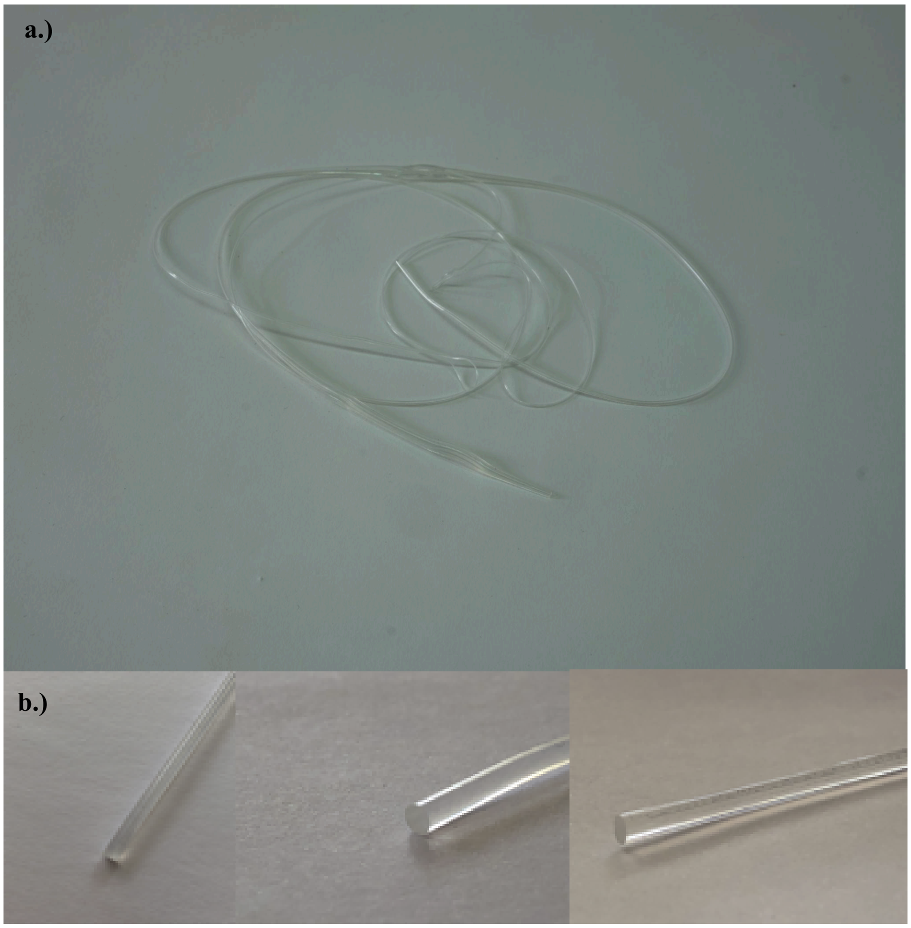


Figure L.5. *a.) The first drawn COC elastomer fibre with two integrated copper wires. b)A selection of the thermally drawn polymeric fibres with more consistent diameters.*

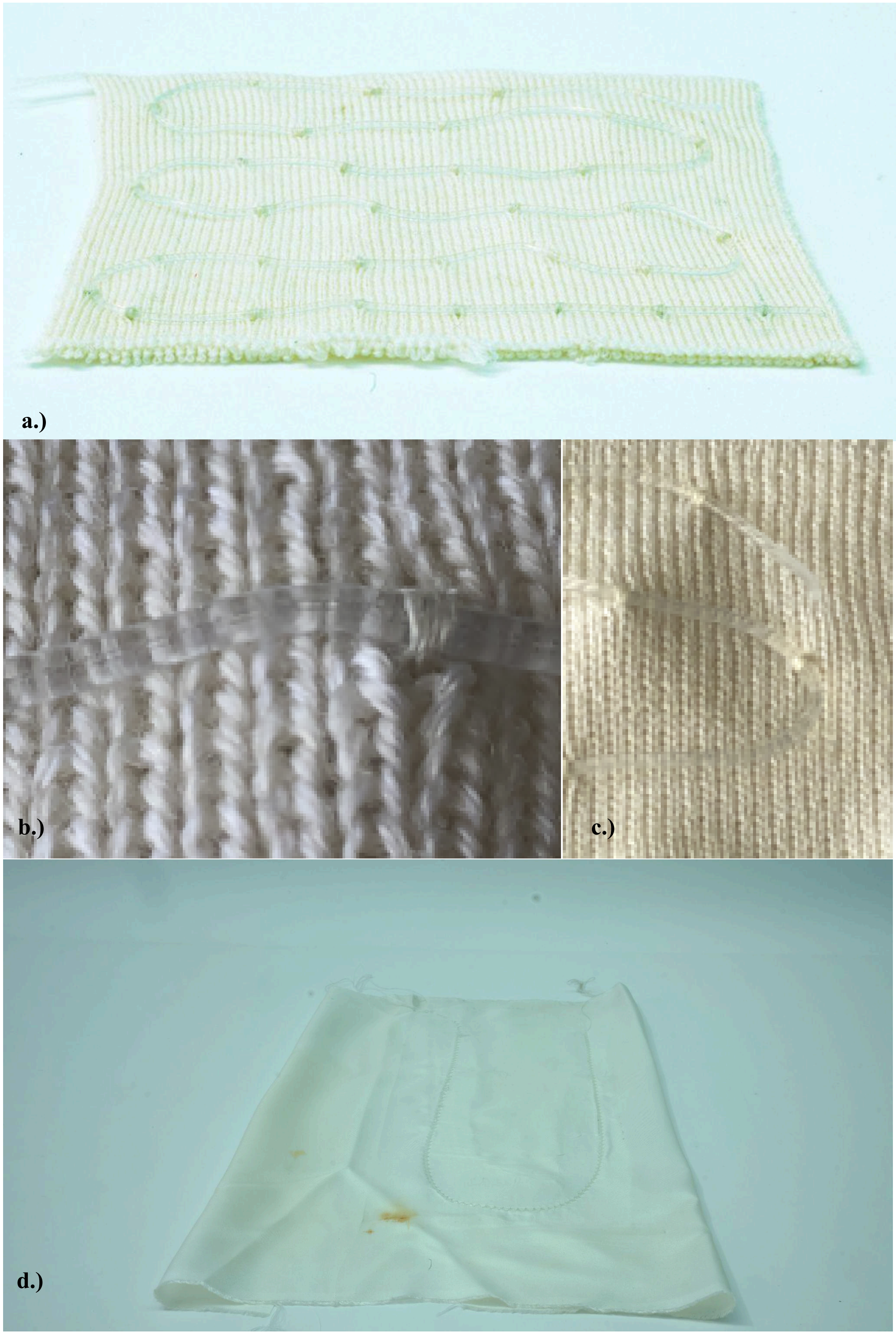


Figure L.6. *a) Thermally drawn polymeric fibre stitched onto a double-bed merino knitted fabric in a curved fashion for demonstrative purposes. b) Close-up of the thermally drawn polymeric fibre stitched across the sample in a curved fashion c.)*

another close-up of the fibre curving across the fabric, pinned in place with stitches. d) thermally drawn fibre embroidered onto silk twill using couching foot on domestic sewing machine and a zig-zag stitch.

L.6 Analysis and opportunities for future work

L.6.1 Position of textile design

The development of the proposal can be attributed to the understanding I gained as a desk-based researcher; embedded researcher and concept developer. The key methods employed, their activities and outcomes together with their associated learning modes are summarised in Table L.1.

Table L.1. Roles, methods, activities, outcomes of textile design within the research study and their associated learning modes

ROLE IN THE PROJECT	KEY METHOD EMPLOYED	ACTIVITIES	OUTCOMES	LEARNING MODE
Desk-based researcher	Literature review	Reviewing literature related to thermally drawn multimaterial fibres and tunable heating mechanisms and their suitability for wearable textiles	Increased understanding of the state of the art as well as foundational knowledge on which concept development could be built	Reading and writing; explicit knowledge 'know-what'
Embedded researcher	Familiarisation	Familiarisation of research culture, set-ting and collaborative partners workloads and methods of working. Physically connecting RCA and ICL	Increased understanding related to the research, production sampling processes and norms related to project devel-opment at the HCRS, ICL	Relational and embodied; 'know-with' and 'know-how'
Concept developer	Synthesis	Identification of textile design opportunities through scientific literature review, collaborative discussion and consultation with technical textile experts at RCA and scientific experts at the HCRS, ICL.	Understanding of where textile design skills and knowledge might usefully be applied	'Know-what' and 'know-how' and 'know-with

Appendix M: Medical/Surgical Tubing Information

NO.	MATERIAL	SUPPLIER	DIMENSIONS AND QUANTITY	NOTES
1.	Platinum-Cured Silicone Tubing	N/A	*QTY: 1. X10M 10M Silicone tubing, platinum-cured 1x2mm.*	ML46131G. RFI# 9531526. PCST/1X3 11532563. PL# 12153413241. Order #: 1152884020-20 19/05/16. ST/AL: 1360291
2.		Trelleborg Polymer Systems Technology	*Description. 025"ID X .011"W X 50'.*	Customer Order Number 310155. Customer Part Number SFM3 — 1550. Manufacturing Part Number SFM3 —1550. TSS World Wide Part Number: HFACC0000 — S6MOY Cure Date 3Q19 Lot Number 201908230061. Short Number 341687. Pack Slip Number 2393065. Country of Origin: United States. Quantity 15.240 MT TSS Northborough Industry
3.		Trelleborg Polymer Systems Technology	*Description . 012" ID X .007"W X 50'. Quantity 15.240 MT.*	Customer Order Number 309481. Customer Part Number SFM3 — 1050. Description. Manufacturing Part Number SFM3 — 1050 . TSS World Wide Part Number: HFAAA0000 — S6MOY Cure Date 3Q18 Lot Number 201809240144. Short Number 341685. Pack Slip Number 2146964. Country of Origin: United States. TSS Northborough Industries.
4.		Trelleborg Polymer Systems Technology	*Description . 012" ID X .007"W X 50'. Quantity 15.240 MT.*	Part Number: SFM3-1750. Quantity: 50 FT (15.24 MTR). Material: SF1664. RML#: 37618
5.		Trelleborg Polymer Systems Technology	*Description . 040" ID X .023"W X 50'. Quantity 15.240 MT*	Customer Order Number: 308949. Customer Part Number: SFM3 — 2050. Manufacturing Part Number SFM3 — 2050 . TSS Worldwide Part Number: HFAEE0000 — S6MOY. Cure date: 3Q17. Lot Number 201709260105 Supplier Number: SF1664 TSS Northborough Life Sci. Label printed 9/26/17. Short Number 341672. Pack Slip Number: 1970973. Country of Origin: United States.
6.		Trelleborg. Sealing Solutions. Northborough Life Sciences.	*Size: .020" ID X .009" WALL. Quantity: 50FT (15.24 MTR).*	Part #: SFM3 — 1350. Material: SF1303. RML #: 35271.
7.		Trelleborg Polymer Systems Technology	*Description . 012" ID X .007"W X 50'. Quantity 15.240 MT.*	Customer Order Number 309481. Customer Part Number SFM3 — 1050. Manufacturing Part Num-ber SFM3 — 1050 . TSS World Wide Part Number: HFAAA0000 — S6MOY Cure Date 3Q18 Lot Number 201809240144. Short Number 341685. Pack Slip Number 2146964. Country of Origin: United States. TSS Northborough Industries.
8.		Saint Gobain Performance Plastics	*2x4 mm code 760160. 1 roll of 50 meters.*	France Site 89120 Charny. Tel. (33) 03 86 63 78 78 4189999. Silicon Tube Versilic. Made in France. Lot: 147927. Tolerance ISO3302-E2. Manufacture: 2015-07. Expiry: 2018-01.
9.	Platinum-Cured Silicone Tubing	Cole Parmer Instrument Company	*ID: .063" OD .125" Wall: .031 L ength: 25FT*	SKU: 95802-02 LOT: 24907061 Date of Mfg: 08/01/2019
10.	Thermoplastic elastomer (TPE)	Saint Gobain Performance Plastics	*ID: 0,040". Wall: 0,033". Length: 3M. QTY: 3M Par Sachet.*	Formulation: Pharmed® BPT — biopharmaceutical tubing. Reference: 070530 —09F. LOT: 3346900. QTY: Info printed on tube: Saint—Gobain pharmacy
11.	Polyvinyl Chloride (PVC)	Winster	*Dimension: 003*006. Length: 1X30M.*	Code Number: 7989985. Batch Number 14Q/14. Label on back: P13/3X6-30M. PVC.
12.	Polytetrafluoro-ethylene (PTFE)	Adtech Polymer Engineering Ltd.	*0,56X 1,07M. 39241 X30 M QTY:1 30M*	XDOCK CTS - NTHTUE BIOBLOCK/1311929445 PTFE microbore tubing

Figure M.1. *Polymeric tubing used in CS2.*

Appendix N: CS2 Material Sample Information

NO.	YARN/ THREAD NAME *(from supplier)*	COLOUR	COMPOSITION	SUPPLIER	SUPPLIER	NOTES
1.	Bobby Syn 120	White	100% PES	*41/19*	Gunold	10,000M CA 45688 12001000020119
2.	-	Purple/Navy COL 1997	100% PES	*135x2*	Madeira	LOT 910624
3.	Cream Frosted Matt Thread	Cream	98% PES, 4% Ceramic	*No. 40 2500 90x2*	Madeira	LOT 913414
4.	POLYNEON	Orange Neon COL 1897	100% PES	*No. 40 DTEX 135*	Madeira	LOT 912424 1000m
5.	-	Dark Green COL 561	100% PES	-	Gütermann	100m/vgs 110 yds
6.	Delta	Dark Green	100% PES	-	English Sewing Delta	Bulked Polyester 47972 BN98291 F&03 80 3884
7.	-	Green	100% PES	*5000M*	Lubrilox	2113 P51 Made in England
8.	Delta	Green	100% PES	*5000M*	English Sewing Delta	Bulked Polyester EZ91463 82847 80 81 F703
9.	-	Cream	100% Mercerised Cotton	-	-	
10.	Gramax	Black COL 09700	100% PES	*Tex 035 5000M*	Coats	Textured Poly Tkt 080 RBJT 21922508
11.	Astra	COL 09700	100% PES	*Tex 027 5000M*	Coats	Staple spun polyester 8754 RBAU 22072249
12.	POLYNEON	Lime Green COL 1950	100% PES	*Dtex 135x2 100M No. 40*	Madeira	Lot: 915914
13.	POLYNEON	Lemon Yellow COL 1823	100% PES	*Dtex 135x2 100M No.40*	Madeira	Lot: 914724
14.	Grilon K-85	Rohweiss	100% PA	*Dtex 840 F68*	Grilon EMS	T/M 100 5001.481 3327 £90/kg
15.	Grilon K-110	Rohweiss	100% PA	*Dtex 840 F68*	Grilon EMS	T/M 100 5001.481 3327 £90/kg
16.	FE-Active	COL 001205	100% VW (Merino)	*Nm 2/60*	Zegna Baruffa Lane Borgosesia	Lot 280340/000016 Qua. Dat 15-Nov-2017 1/3
17.	POLYNEON	Lime Green	-	-	-	-
18.	Rubco	Rubco with black polyester core Black	100% PUR	*dTex 4400*	Rubco	Nr 2113 Charge 4924
19.	Rubco	Rubco with stainless steel core	100% PUR	*dTex 9500*	Rubco	Nr 2255 Charge 4912
20.	Bianco	Bianco	38% Cotton, 12% Nylon, 50% PUR	-	Luigi Boldrini srl	LOT 3639

Figure N.1. *Embroidery yarn and thread used in CS2*

NO.	SUBSTRATE NAME (from supplier)	COLOUR	COMPOSITION	SUPPLIER	NOTES
1.	Stretch Net Anzio	White	100% PA	Whaleys	195cm wide £13.40 p/m from RCA college shop
2.	Tropical	White	100% Silk	Biddle Sawyer silks	£14.00 p/m
3.	-	White	100% Lycra	Carrington Fleet Textiles Ltd.	£5.00 p/m
4.	Interlining	White	100% Cotton	Carrington Fleet Textiles Ltd.	£4.80 p/m
5.	Backing iron-on stabiliser model 1640B	White	-	Gunold	£65.30 p/roll vat exclud. 48g 100 x 105cm
6.	Solvey	White	-	Solvey	100m x 100cm roll. Solvey roll £71.00 vat exclud. Water soluble film that dissolves on contact with water or steam

Figure N.2. *Embroidery substrates used in CS2.*

NO.	SUBSTRATE NAME (from supplier)	COLOUR	COMPOSITION	SUPPLIER	NOTES
1.	SETOR Monofilament	White	100% PES	TWD Fibres	Y GL E0776F2y/1 FNR:8020 FNA: Reinweiss Mat: B7101534 Charge: 0000161623
2.	Fluid	White	91% Viscose 7% PA 2% Elastane	Yeoman Yarns, Leicester	300gm cone 4800m
3.	Polo	White	100% VW (Merino wool)	Yeoman Yarns, Leicester	£5.00 p/m

Figure N.3. CS2 *Knitted textiles yarn information.*

METHOD OF INTEGRATION CODE	METHOS OF INTEGRATION NAME
a.	Knit
b.	Weave
c.	Embroider—ZSK stitch
d.	Embroider—ZSK cording device
e.	Knit Domestic cording foot
f.	Domestic doublehead needle stitch
g.	Coverstitch
h.	French knit braid 10g every second needle (half gauge) if every needle then 12g
i.	Braid
j.	Ultrasonic
k.	Iron
l.	RF

Figure N.4. *CS2 Methods of textile integration.*

Appendix O: CS2 Textile sampling technique rationale

METHOD	TECHNIQUE	SAMPLE NOS.	DECRIPTION	DECRIPTION	RATIONALE
Embroidery /stitch-based methods	Couching	1-9	Lays cables or cords onto fabric, secured by threads, trialed on domes-tic and industrial machines	Customisable tubing layout; supports varying curvatures; works on various substrates; simplifies attachment by integrating stitching and tubing.	Risk of tubing puncture due to needles.
	Running stitch	10	Stitches two mesh layers to form channels.	Customisable tubing layout; supports varying curvatures; works on various substrates.	Requires manual tubing feed.
	Twin-needle embroidery	11-13	Domestic sewing machine attachment stitching parallel lines with zigzag on the reverse	-Customisable tubing layout; supports varying curvatures and substrates; - Ability to attach polymeric tubing to the substrate during stitching in a single step, simplifying the process and eliminating the need for manual threading.	Risk of tubing puncture due to needles.
	Cover stitch	14-23 & 34-39	Seaming and finishing method for stretch and knitted jersey fabrics.		
Knit-based methods	French braiding	26-33	Fabricates knitted tubes.	Using 'fixative' yarns offers an alternative to stitch based attachment method; no puncture risk as tubing is manually fed through channels.	Requires manual tubing feed.
	Weft-based knitting	34-50	Flat knitting process. Used in this study for plating, interlocking, rib, milano, and tubular structures.	- Stretch; body-conforming; - Secures tubing close to skin; Allows fibre/ structure-level adjustments to target performance (e.g., wicking yarns in perspiration zones).	

Figure O.1. CS2 *Textile sampling technique rationale.*

Appendix P: CS2 Material sampling information - Embroidery and mixed media

The embroidered and mixed media samples were produced at the RCA in the Mixed Media Textile Design Workshops and the Menswear Fashion Studio, using the following equipment:

- The digital embroidery machine ZSK Racer 1W (Adobe Illustrator, Wilcom, and Ethos-aps software);
- Bernina 1008 domestic sewing machine;
- Brother FD4-B272 coverstitch machine;
- Kansai Special W-8003D coverstitch machine.

P.1. Technique Progression Overview:

P.1.1 Couching Technique:

- Initially conducted on the Bernina 1008 using a couching foot (Sample 1). This setup did not allow for tight curves, leading to its discontinuation.
- To explore higher fidelity designs I moved to the Digital Embroidery Machine (ZSK Racer 1W with Ethos-aps software).
- Samples 2-6 used the following materials:
    - Tubing (2);
    - Substrate (4) to test embroidery design without interference from a stretch substrate.
    - Thread (5) chosen for stitch visibility;
    - Stitch values (lengths) explored varied from 1.5 to 2.3mm to avoid tubing puncture.
- In sample 7, I switched substrate to (1), backed with (5). Sample 8 changed tubing to (9) and substrate backing to (6) and sample 9 adjusted tubing to (1) and stitch width was minimised.
- Despite iterations, the risk of tubing puncture using this approach remained too high due to the needle presence, making this automated technique unsuitable for fluidics.

P.1.2. Alternative Cording Technique:

- Utilising a two-pronged needle embroidery foot on the Bernina 1008 domestic sewing machine, I sought to overcome the risk of puncture that emerged in previous samples and create channels between two pieces of substrate (1) in sample 10. Initial trials threading tubing (10) through the channels post-stitching were challenging due to tight curves within the design and so I explored integrating tubing (10) whilst stitching (samples 11-13). This technique minimised risk of puncturing but was limited to tubing that fits between the needles.

P.1.3. Coverstitch Technique:

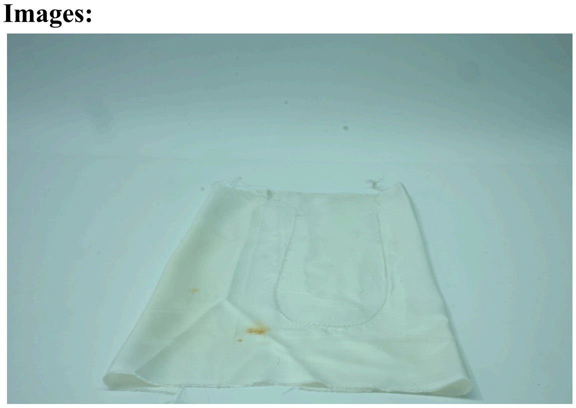
- Samples 14-21 were produced in the Menswear Fashion Studio using the coverstitch machine, where I fed various tubing sizes between the needles under the fabric (1). Although aesthetically pleasing, turning corners without puncturing the tubing remained challenging. Samples 22&23 explored a similar concept without using a substrate.

P.1.4. Incorporating Low Melt Nylon yarns into Knitted Textile and Coverstitch Techniques:

- Samples 24-39, produced in the Mixed Media Textile Design Workshops, used low melt nylon yarns (14&15) as a knitted substrate (samples 24-25), knitted-tube (samples 26-33) and a backing yarn for the coverstitch technique(33-39). This method was interesting but impractical for skin contact due to insufficient tube exposure and unappealing fabric backside.

P.1.5. Ultrasonic welding:

- Samples 39-42, explored in the Mixed Media Textile Design Workshops, tentatively patch test toward the idea of sealing a tube within waterproof fabric to eliminate the need for integrating tubing post-knitted textile construction using ultrasonic welding. Although interesting, this concept was not deeply explored due to time constraints and a focus on knitted samples.

Sample#: 1	**Tubing:** COC fibre (see Appendix L&U).
Yarns/threads: 1	**Substrate:** 2&5
Method of integration: E	
Comments: I attached the COC to silk twill using a zigzag stitch, stabilising the fabric with an iron-on backing to prevent distortion. A domestic cording foot enabled quick testing without digital setup, making the process simple but limited. It worked well for wider curves and straight lines but struggled with tight shapes and risked puncturing the tubing, unsuitable for precise designs. Best for larger, simple areas like the body, it lacked the precision of industrial machines. Thread and backing colors could be matched for subtle effects, but this approach is ideal for low-precision prototypes	
Images:  	

Sample#: 2-6	**Tubing:** 9
Yarns/threads: 1&2	**Substrate:** 4

Method of integration:

Comments:

Five samples tested varying stitch lengths to reduce tube piercing:
1.5mm
1.8mm - Adjusted stitch length.
2.3mm - Further adjusted stitch length.
2.3mm - Rotated design to test tighter turns using up/down vs. left/right movement.
2.3mm - Design rotated again; tubing fed through smaller hole feed but halted as tubing couldn't move freely, leading to piercing.

Tighter turns increased puncture risk; wider turns/straight areas had fewer punctures.

- Stitch length 2.3mm reduced piercings.
- Rotating design had minimal impact on punctures.
- Puncture risk remains due to needle use; optimising stitch length, substrate, and design could reduce it.
- Subtle thread colours may improve visual blending with the substrate.

Images:

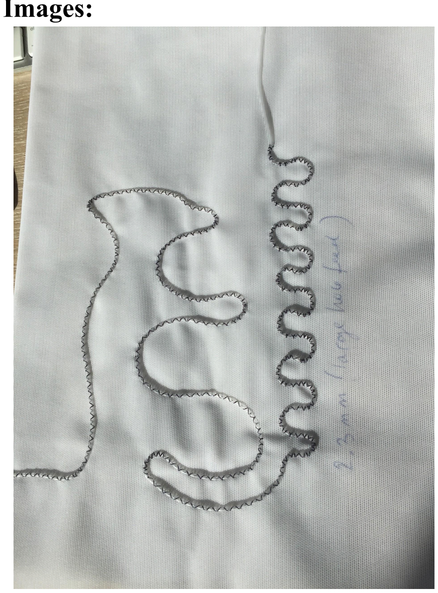
Sample#: 7	**Tubing:** 2
Yarns/threads: 1&2	**Substrate:** 1&5

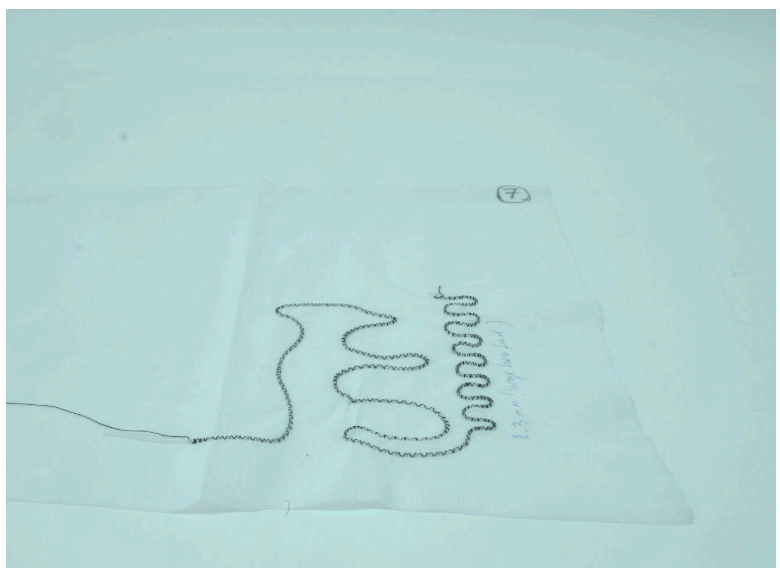
Method of integration: D

Comments:
Switched to stretch nylon mesh (1) for its conformability, tubing placement, and sporty aesthetic—ideal for close-fitting garments. Used the same design file and 2.3mm stitch value.

- **Integration:** Stabilised substrate (1) with backing (5) during stitching.
- **Ease of Use:** Poppers or zips may be needed for easy wear, removal, and size adjustments.
- **Finishing:** Fine finishing required to maintain the lightweight aesthetic.
- **Backing:** Substrate (5) was hard to remove post-stitching.

Images:



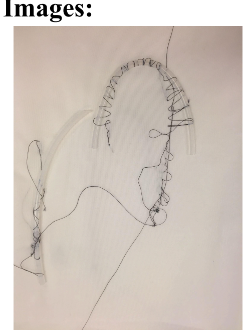


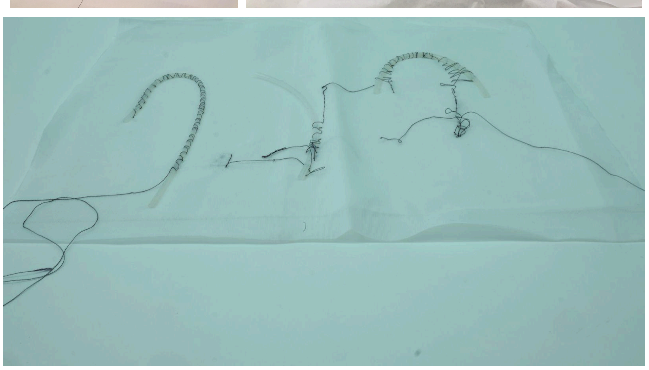
Sample#: 8	**Tubing:** 9 (x2 lengths tied together to fit ZSK length requirements).
Yarns/threads: 1&2	**Substrate:** 1&6
Method of integration: D	

Comments:
Tested thicker tubing using a curved line digitised in Wilcom software and stitched with a ZSK machine (6mm cording width). Substrate (5) switched to dissolvable backing due to removal issues with the previous backing.

- Narrow bobbin gap caused sticky tubing to catch fabric.
- Tubing fit the larger feeder hole but slipped during stitching.
- Thicker tubing didn't resist needle punctures.
- Manual bobbin adjustments were unsuccessful.
- Thicker tubing unsuitable for ZSK machine but visually appropriate for fabric.
- Tubing size may need to vary by body area (e.g., smaller for arms) to improve flexibility.
- Exploring variable tubing sizes across designs could enhance functionality and adaptability.

Images:



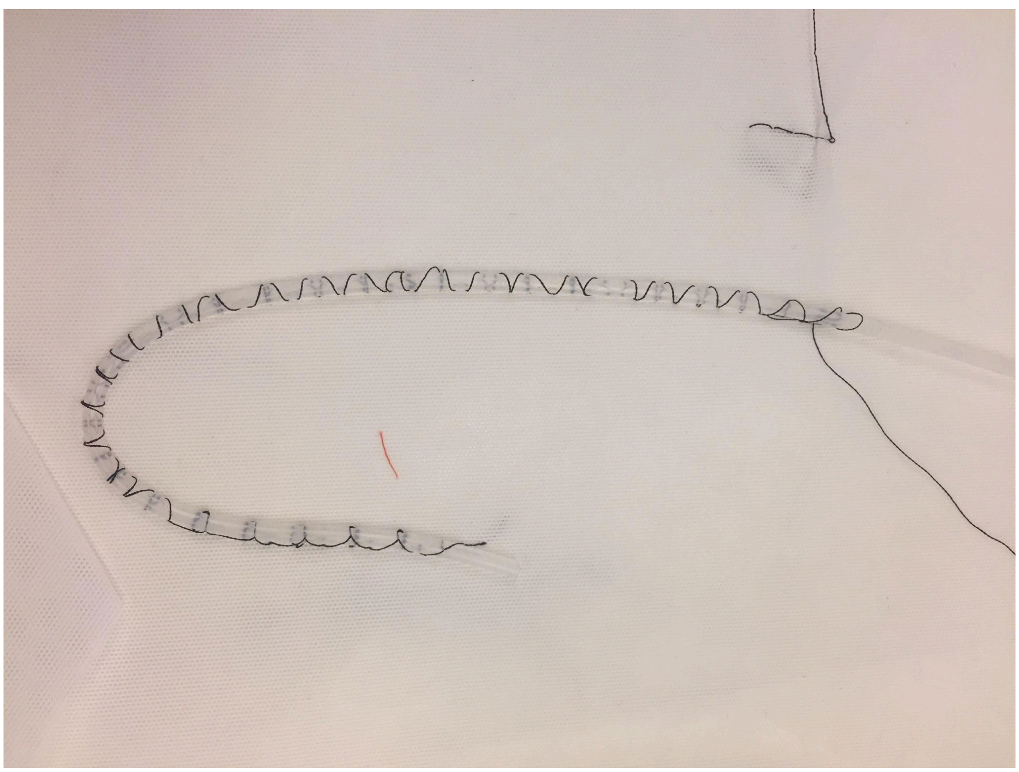


Sample#: 9	**Tubing:** 1
Yarns/threads: 1&2	**Substrate:** 1&6
Method of integration: D	

Comments:
Same design as the previous sample, tested with finer tubing (1) and 4mm cording stitch width.

- Feeder couldn't hold silicone tubing, causing it to spill out unless manually held.
- Tubing punctured on corners but not on straight lines.
- Swatch failed due to tubing being too large for the ZSK machine, though it appeared suitable for the fabric and application.
- Tubing size may need to vary by body area (e.g., smaller tubing for arms for flexibility and ease of use).
- Exploring variable tubing sizes across designs could enhance flexibility and functionality

Images:



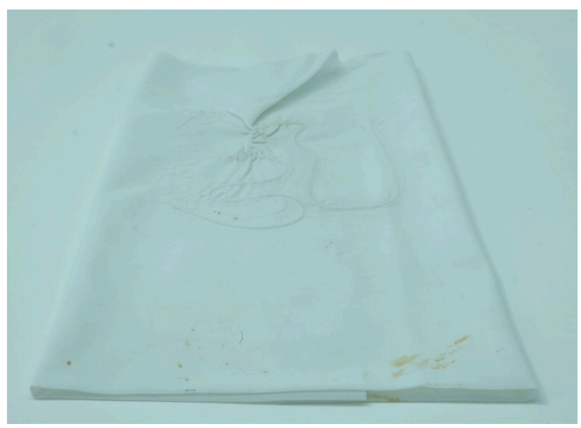
Sample#: 10	**Tubing:** 9
Yarns/threads: 1	**Substrate:** 1&6

Method of integration: C

Comments:
This sample aimed to prevent needle punctures by stitching parallel lines through a double layer of nylon stretch mesh, creating channels for threading tubing post-stitching. The design was functional but rough and could be refined.

- Threading tubing through channels was difficult due to the mesh's stretch and the tubing's stickiness, causing the tubing to snap after covering a third of the design.
- The tight design, stretch mesh, and sticky tubing made this technique too time-intensive.
- Open mesh holes raised concerns about the tubing's necessary proximity to the skin.
- The sample inspired jacquard design ideas and a subtle aesthetic where functions are not immediately visible, offering potential for future woven swatches.
- Adjusting the design for less tightness and using proper threading tools (e.g., for spaghetti straps) could improve feasibility.
- Pockets in woven fabrics with a more open weave on one side might enhance skin contact.
- While unsuitable for this application, the pulled, ruched effect from tight channels and sticky tubing, combined with the white mesh and slightly off-tone cream stitching, presented positive aesthetic elements for further development

Images:



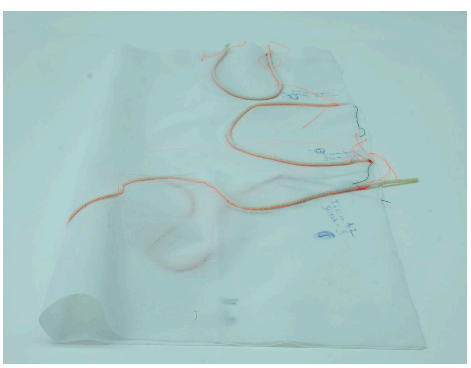
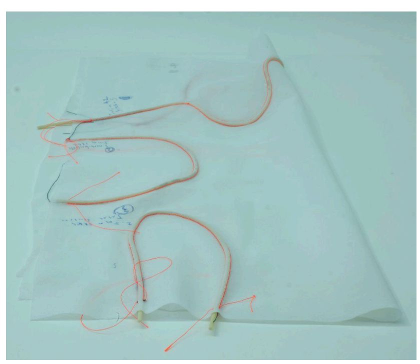
Sample#: 11-13	**Tubing:** 10
Yarns/threads: 4&5	**Substrate:** 1&6
Method of integration: F	

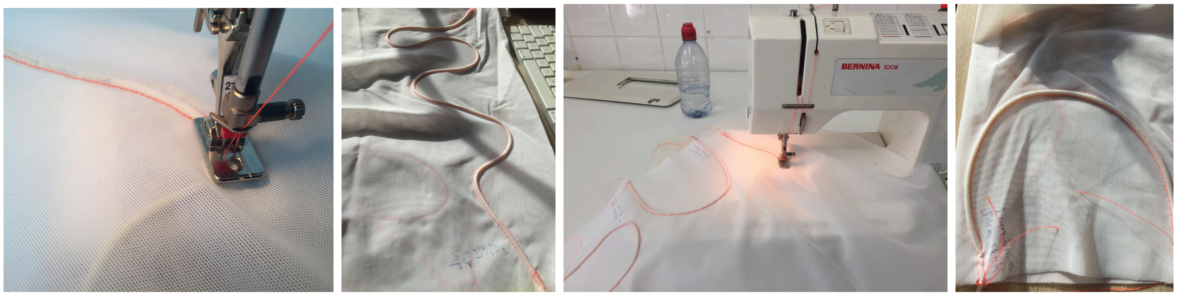
Comments:
These samples tested the double needle-head on the Bernina to stitch on either side of the tubing while feeding it through simultaneously, eliminating post-stitch threading.

Sample Testing:

- **Sample 1:** Tension 4.2, Stitch Length 5mm
- **Sample 2:** Tension 5, Stitch Length 5mm
- **Sample 3:** Tension 5, Stitch Length 2.5mm
- The tube fed smoothly between the two needles beneath the fabric, with the needle distance matching the tube (10) width.
- Tube material, less sticky than silicone, reduced handling issues.
- Backing (6) was washed away post-stitching.
- Needles consistently stitched on either side of the tube, minimizing puncture risk compared to previous hopping methods.
- The running stitch on nylon stretch mesh performed well and could replace zigzag stitching, improving compatibility with stretch fabrics without losing functionality.
- Neon colors on a black substrate were visually striking, enhancing tube visibility and evoking Anna Talvi's antigravity clothing. Alternatively, subtler designs could conceal integrated technology.
- Tubing size is limited to what fits between the two needles unless a custom needle head is developed.
- Future innovations might explore pocketed weaving or knitting to accommodate larger or differently shaped tubes.

Images:


BERNINA

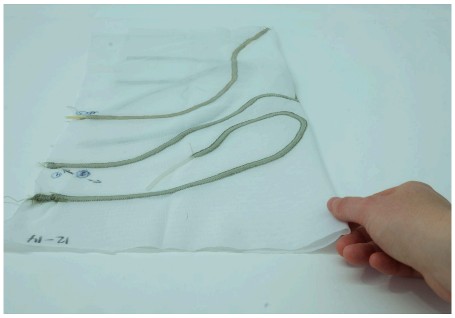
Sample#: 14	**Tubing:** 1
Yarns/threads: 6,7,8	**Substrate:** 1&6

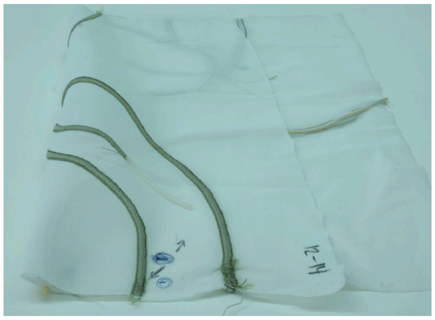
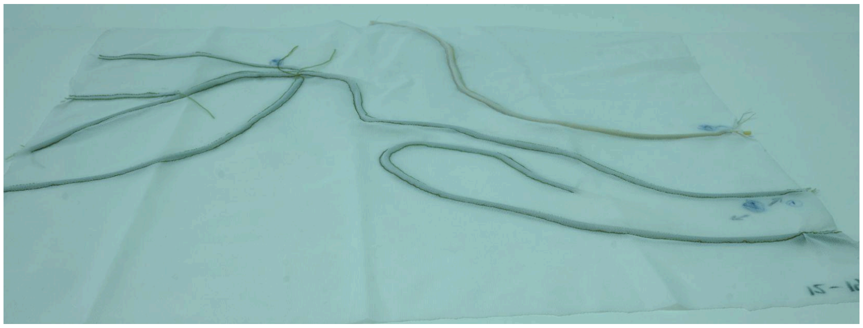
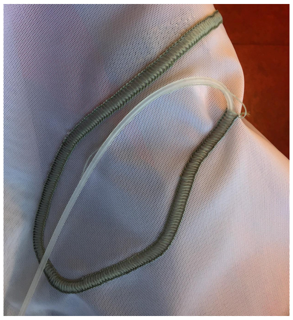
Method of integration: G

Comments:
Building on the previous sample, this sample used the coverstitch machine with a half-inch setting.

- Tube was fed between the two coverstitch needles on the underside of the fabric. Substrate (6) was added under the stretch mesh to prevent tubing from sticking to the machine's metal surface.
- Yarns were difficult to thread, and the slightly thicker tube fit snugly but stuck to the metal plate.
- Turning corners was challenging, occasionally causing needle misalignment and tubing punctures.
- The samples were visually appealing, repurposing coverstitch—a finishing technique—for functionality by placing it at the fabric center rather than the edge, creating a familiar yet unexpected aesthetic.
- Coverstitching offered a slightly better alternative to embroidery machines, with reduced puncture risk, though needle presence still posed a threat.
- Using less sticky materials or additional stabilisers may mitigate stickiness issues.
- Developing tools or techniques for corner handling and needle alignment could reduce punctures.
- The innovative use of familiar techniques in unconventional ways shows aesthetic promise and warrants further exploration.

Images:



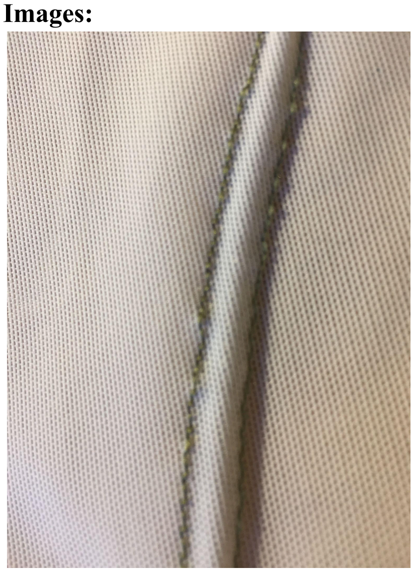




Sample#: 15	**Tubing:** 9
Yarns/threads: 6,7,8	**Substrate:** 1&6
Method of integration: G	

Comments:
Same process as above, yet different tubing.

- The silicon tubing was slightly thinner than previous samples. I experimented with stopping the machine to pass over another tube, creating overlapping designs. While possible, this technique is limited by the foot’s ability to pass over existing tubing and the space for new tubing underneath.
- Increasing levels of skin contact might be necessary, and bulky yarn may not be ideal as it occupies more surface area.

Images:

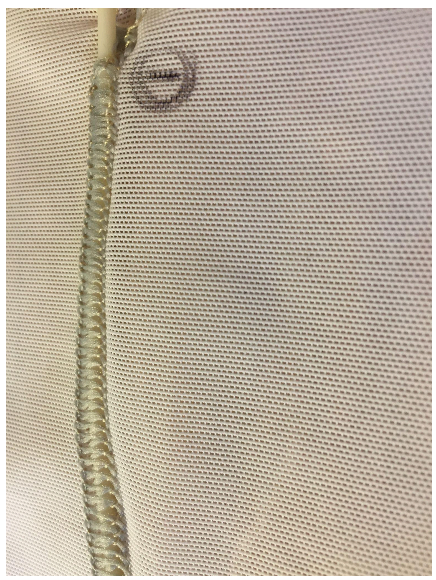


Sample#: 16	**Tubing:** 10
Yarns/threads: 6&9	**Substrate:** 1
Method of integration: G	

Comments:

Similar as above yet different tubing, which felt more sturdy, this may have been the polymer or a thicker wall.
Material was easier to work with than the others in this series.
Aesthetically appearance is not as promising as previous swatches in this series on account of combination of cream thread and tube.

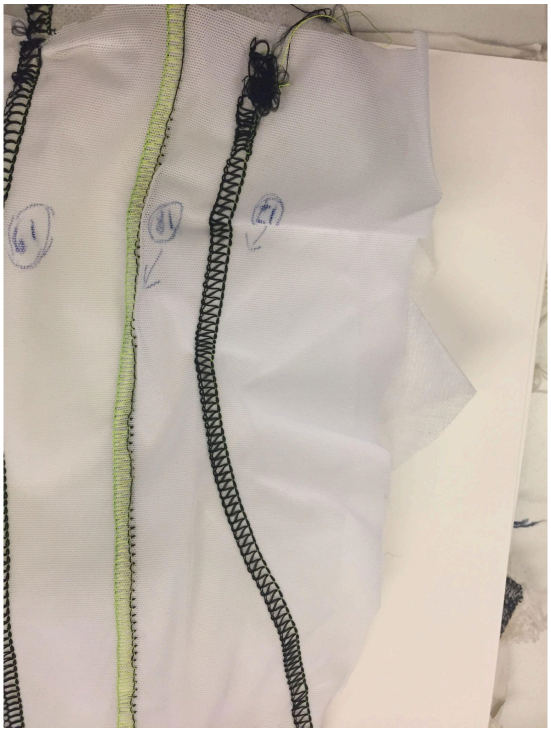
Images:

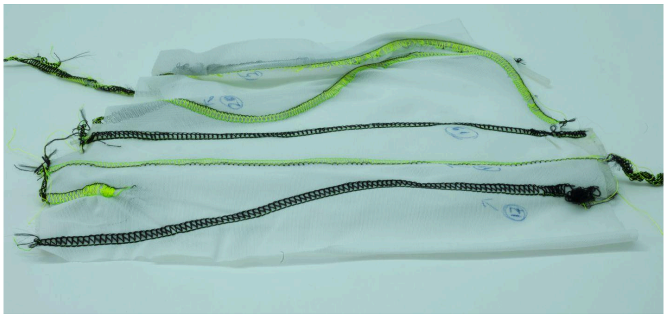


Sample#: 17	**Tubing:** N/A
Yarns/threads: 10,11,12	**Substrate:** 1&6
Method of integration: G	

Comments:
Ran cover stitch as an exploration on the fabric, without tubing

Images:





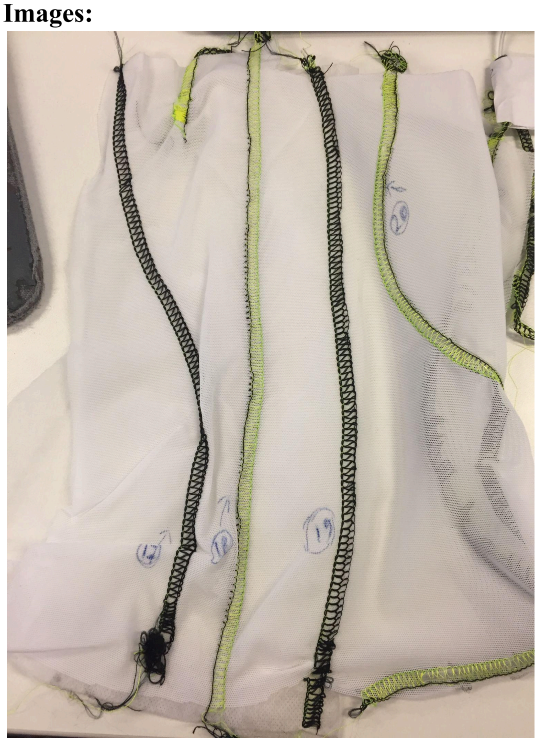
Sample#: 18	**Tubing:** 2
Yarns/threads: 10,11,12,13	**Substrate:** 1&6
Method of integration: G	

Comments:
In this sample, the fine tube was fed between two layers: stretch mesh and dissolvable backing, with a 4th thread used as a decorative top thread.

Unlike the previous sample, the back thread was placed under the mesh, causing the tube to protrude below the black thread. Reversing this arrangement would have allowed the tube to contact the skin through the looser, finer neon yellow decorative thread.

The black thread created a strong contrast against the white background, which felt too harsh, further amplified by the bulking yarn, intensifying the contrast.

Images:



Sample#: 19	**Tubing:** 2
Yarns/threads: 10,11,12,13	**Substrate:** 1&6
Method of integration: G	
Comments: The tube was fed between two layers—stretch mesh and dissolvable backing—while using a 4th thread as a top decorative stitch. The tubing was positioned to be revealed under the lemon neon yellow decorative stitch on the skin side. This sample featured a straight lemon neon yellow decorative stitch to test tube thickness. However, the black thread created excessive contrast against the white background, further amplified by the bulking yarn, making the contrast more pronounced	
Images: 	

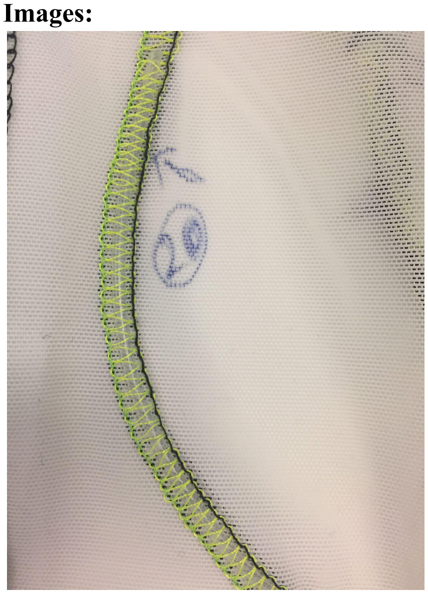
Sample#: 20	**Tubing:** 1
Yarns/threads: 10,11,12,13	**Substrate:** 1

Method of integration: G

This piece featured a lemon neon yellow decorative stitch on the skin side and explored curvature. The tube was placed on top of the stretch mesh and beneath the decorative stitch, with no dissolvable backing used for guidance.

- The 'tunnel' created had ample space on either side of the tube, possibly too much, but the face side of the sample looked good.
- The black back yarn was overly fluffy, detracting from the sleek look.
- Tubing was pierced on some curves due to stitching too quickly.
- The fine neon yellow decorative stitching provided multiple openings for tubing to be revealed, which were more effective than those created by the coverstitch alone.
- While the decorative stitch openings are visually appealing, they add slight weight to the piece.
- Refining the black back yarn could improve the sleekness.
- The black, yellow, and white color combination was unappealing; a revised palette could enhance visual harmony.
- Slowing down stitching, particularly on curves, may help prevent tubing puncture

Images:

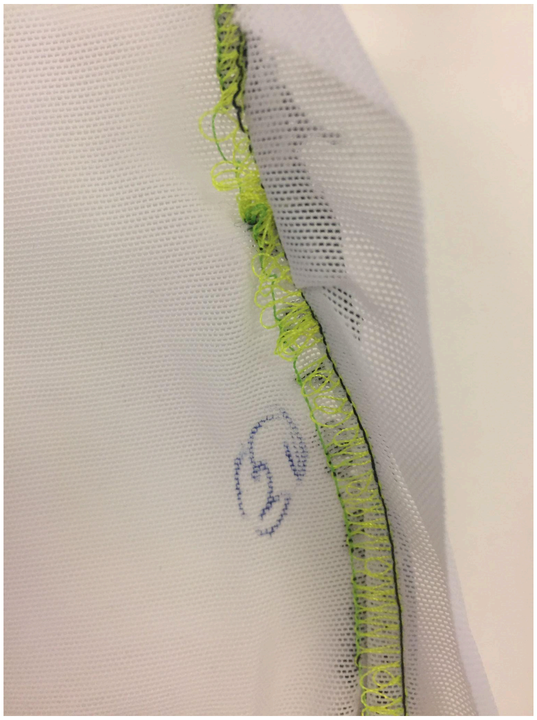


Sample#: 21	**Tubing:** 9
Yarns/threads: 10,11,12,13	**Substrate:** 1
Method of integration: G	

Comments:
This sample used a much thicker tube, fed through on the underside of the fabric, which was likely a mistake. The tube's weight distorted the fabric significantly, potentially causing gaping or moving the tubing away from the body. Stitches popped out, possibly due to the tube's thickness or the threading.

- Thicker tubing distorted the fabric and may not sit close to the body as intended.
- Feeding the tube on the underside may have contributed to popping stitches.
- Redo this sample with the tubing fed under the decorative stitch above the fabric, as in the previous swatch, to better evaluate aesthetics and functionality.
- Reassess the tubing thickness, as it seems too bulky, impacting both structural integrity and visual appeal

Images:



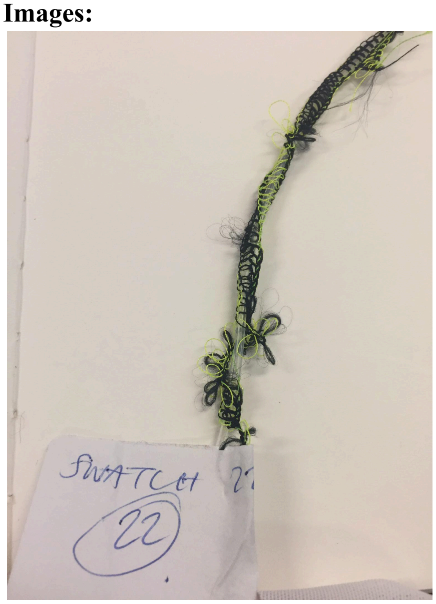
Sample#: 22	**Tubing:** 9
Yarns/threads: 10,11,12,13	**Substrate:** N/A
Method of integration: G	

Comments:
This swatch explored feeding the tube into the coverstitch tail without attaching it to the fabric at that point, inspired by the way the machine tails off during stitching. This idea informed subsequent experiments and emerged organically through the making process.

The swatch is too messy to evaluate its aesthetic potential accurately. The colours clash, and while some areas are successful, they are sparse. Frequent breaks in the feed result in an unpredictable, inconsistent swatch that would be difficult to replicate without significant time investment.

- The concept of feeding the tube into the coverstitch tail is promising and worth further exploration.
- Current inconsistencies make it unreliable; refining the technique or adjusting materials could improve outcomes.
- Reconsider the colour palette for better visual harmony.
- Future experiments should aim for greater reliability and consistency to achieve a more polished and replicable aesthetic.

Images:



Sample#: 22a	**Tubing:** 9
Yarns/threads: 10,11,12,13	**Substrate:** N/A

Method of integration: G

Comments:
This swatch experimented with a longer coverstitch tail than the previous one. However, gaps and broken or unattached stitches persisted, likely due to machine limitations or speed. Curling in many areas led to inconsistencies in the front/back of the coverstitch. Despite these issues, the successful areas were visually impressive and showed potential for further development.

- The swatch is too inconsistent to evaluate its aesthetic value accurately.
- Sparse successful areas and frequent feed breaks result in an unpredictable outcome.
- Future work should focus on stabilizing the coverstitch tail, possibly using adhesive yarn to enhance attachment and improve appearance.

Images:

<table>
<tr><td>Sample#: 23</td><td>Tubing: 2</td></tr>
<tr><td>Yarns/threads: 10,11,12,13</td><td>Substrate: N/A</td></tr>
<tr><td colspan="2">Method of integration: G</td></tr>
<tr><td colspan="2">Comments:
Similar to the previous swatch, this sample featured a long coverstitch with a smaller tube fed through while the machine was running. However, the stitching twisted, likely due to inconsistent machine speed, causing threads to break and preventing a proper coverstitch. The technique appeared slightly more effective with thicker tubing, especially at the half-inch setting.

● Refining the technique to stabilise the tube and maintain consistent machine speed could improve results.
● Experimenting with different tubing sizes may lead to more reliable and visually appealing outcomes.</td></tr>
<tr><td colspan="2">Images:</td></tr>
</table>

Sample#: 24	**Tubing:** N/A
Yarns/threads: 14	**Substrate:** N/A
Method of integration: A	

Observations:
Used 2 ends of (14), a low-melt nylon, on an 8-gauge B Dubied hand flat knit machine. Initial tension was 13, adjusted to 12.5, then back to 13, with the entire piece knitted at tension 12. The yarn occasionally stuck on the cone, requiring monitoring. It produced a visually stunning brilliant white colour.

Considerations:
The brilliant white is striking but the low-melt nylon's distinct feel, lack of breathability, and weight may limit its suitability for close-to-skin garments. A sock over the cone is recommended to prevent sticking during knitting. Future experiments could focus on its use in outer layers or as decorative elements

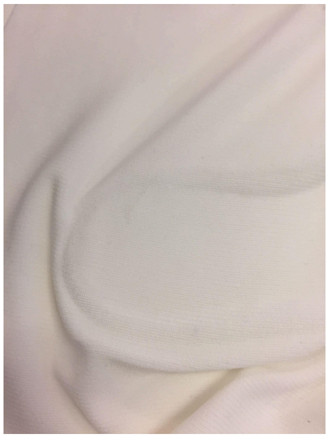
Images:

Sample#: 25	**Tubing:** N/A
Yarns/threads: 14	**Substrate:** N/A
Method of integration: A	
Observations: Began at tension 13, adjusted to 12, then knitted at 12.5. The drawstring edge remained too loose. The brilliant white colour is visually striking, but the low-melt nylon feels heavy and lacks breathability, making it unsuitable for close-to-skin layers. Tension adjustment to 12.5 improved results, but the drawstring edge needs further tightening. The yarn's texture and breathability limitations restrict its use for close-to-skin garments. Using a sock can help manage tension and prevent sticking. Refining tension settings and exploring alternative applications may enhance its usability.	
Images:	

Sample#: 26	**Tubing:** 8
Yarns/threads: 14	**Substrate:** 3
Method of integration: H&K	

Observations:
The concept of feeding the tube through is innovative, enabling potential replacement if needed. However, the structure may need to be more open to improve skin contact. The yarn’s brilliant white colour is visually striking, but the low-melt nylon feels heavy and lacks breathability, making it unsuitable for close-to-skin layers. Increasing the structure's openness could enhance skin contact and comfort. The yarn's texture and weight restrict its use for close-to-body garments. Further adjustments are required for optimisation.

Images:



Sample#: 27	**Tubing:** 11
Yarns/threads: 14	**Substrate:** 3
Method of integration: H&K	

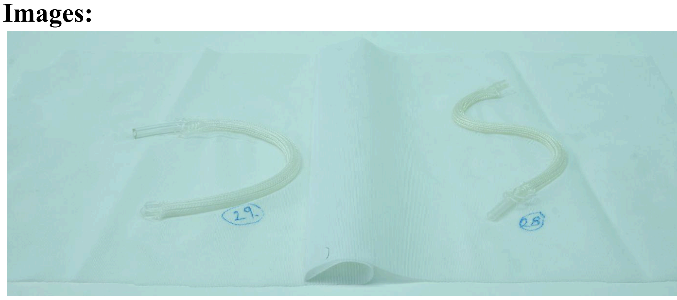
Observations:
French braided a tube using yarn (14) (10g with half needles; would be 12g with all needles). Fed a PVC tube into it, which was easier than with silicone. Fused the tube to the fabric underside by ironing for 20 seconds with a Teflon layer.The tube design is novel, allowing for potential replacement, but the structure may need to be more open to improve skin contact. The yarn's brilliant white colour is visually stunning, but its distinct feel, lack of breathability, and heaviness make it unsuitable for close-to-skin layers.
The structure should be more open to enhance skin contact. While the yarn's brilliant white is visually appealing, its texture and breathability limit its use for close-to-skin applications

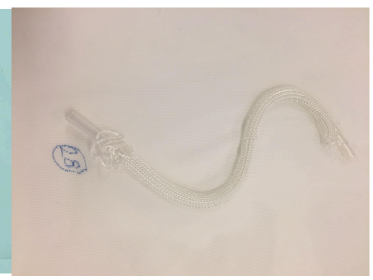
Images:

Sample#: 28	**Tubing:** 8
Yarns/threads: 14	**Substrate:** 1
Method of integration: H&K	

Observations:
The tube was constructed as in the previous sample, with a silicone tube fed into the French braided low-melt nylon yarn. The stickiness of the silicone made feeding difficult, unlike the easier handling of the previous PVC tube.
The fusing temperature must be low enough to prevent silicone tubing damage. The oily texture of low-melt nylon, while essential for fusing, may not be ideal for skin contact. Exploring zonal application or alternative materials could improve functionality and user comfort.

Images:





Sample#: 29	**Tubing:** 11
Yarns/threads: 14	**Substrate:** 1
Method of integration: H&K	

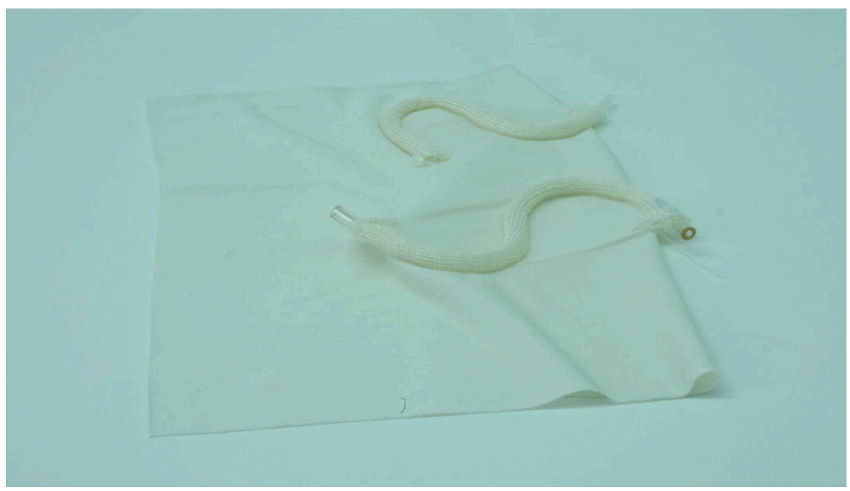
Observations:
The PVC tube, fed into the French braided tube, was sticky, making it somewhat challenging to feed through. The nylon was fused to the fabric underside using an iron for 20 seconds with a Teflon layer in between.
The tight knit of the low-melt nylon may not be suitable for skin contact, and its oily texture raises additional concerns. While necessary for fusing, a more open structure (e.g., using every third needle) or zonal application could improve usability but may be labor-intensive. Exploring a more manufacturable alternative is recommended. Care must be taken to use a fusing temperature that avoids damaging the PVC tubing.

Images:

Sample#: 30	**Tubing:** 8
Yarns/threads: 14&16	**Substrate:** 1
Method of integration: H&K	

Observations:
This swatch used a French braided tube made from low-melt nylon yarn (14) combined with FE active-treated merino wool to enhance thermoregulation and handfeel. The sticky silicone tube was somewhat difficult to feed through. The braided tube was fused onto the fabric underside with an iron for 20 seconds, using a Teflon layer. The merino wool improved breathability and handfeel but resulted in a tight knit. Using every third needle could create a more open structure. Yarn 14, while necessary for adhesion, has an oily feel and may be too hot for skin contact, highlighting the need for more breathable yarns. A zonal approach during the French braid process or an alternative method could simplify manufacturing. Lower heat settings are crucial to avoid damaging the silicone tubing during fusing.

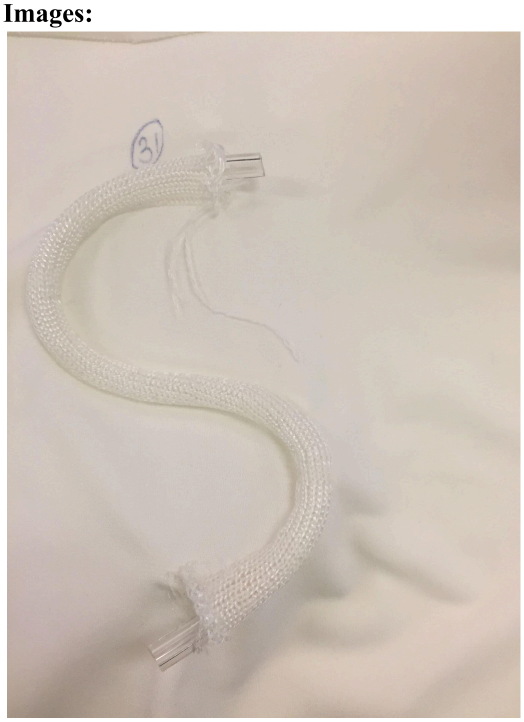
Images:



Sample#: 31	**Tubing:** 11
Yarns/threads: 14&16	**Substrate:** 3
Method of integration: H&K	

Observations:
French braided tube made from yarn 14 combined with FE active-treated merino wool to enhance thermoregulation and handfeel. The sticky PVC tube was somewhat difficult to feed through. The braided tube was fused to the fabric underside using an iron for 20 seconds with a Teflon layer.
The merino wool improved breathability and handfeel, but the knit remained too tight. Using every third needle could create a more open structure. While K85 yarn is essential for adhesion, its oily feel may be uncomfortable against the skin, highlighting the need for more breathable yarns. Exploring zonal application during the French braid process or a more manufacturable alternative could improve usability. Fusing temperature must be carefully controlled to avoid damaging the PVC tubing.

Images:

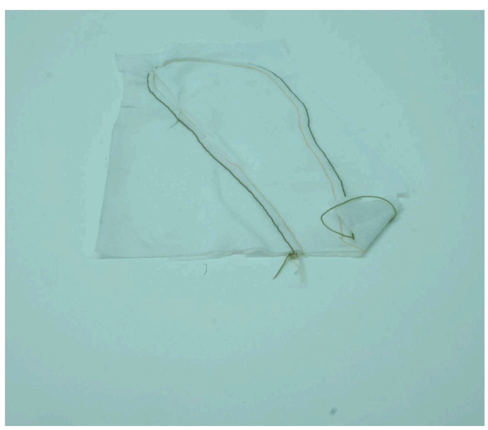


Sample#: 32	**Tubing:** 8
Yarns/threads: 14&16	**Substrate:** 1
Method of integration: H&K	
Observations: I French braided a tube using yarn (14) with FE active-treated merino wool (16) to enhance thermoregulation and handfeel. Feeding the sticky PVC tube through the braid was challenging. The tube was fused to the fabric with an iron for 20 seconds, using a Teflon layer. Merino wool improved breathability and handfeel, but the knit remains too tight for skin contact. Using every third needle could create a more open structure. Yarn (14) is necessary for adhesion, but its oily texture and heat retention make it unsuitable for direct skin contact. Exploring alternative materials or a more open knit design could enhance breathability and comfort. Fusing temperature must be carefully managed to avoid damaging the PVC tubing.	
Images:  	

Sample#: 33	**Tubing:** 11
Yarns/threads: 14&16	**Substrate:** 1
Method of integration: H&K	

Observations:
A French braided tube (10g with half needles, 12g with all needles) was made with yarn 14 (low-melt nylon) and FE active-treated merino wool to improve thermoregulation and handfeel. Feeding the sticky PVC tube through was difficult. The tube was fused to the fabric with an iron for 20 seconds using a Teflon layer.
Merino wool improved breathability and handfeel, but the knit is too tight for skin contact. Using every third needle could create a more open structure. While K85 yarn is necessary for adhesion, its oily texture and heat retention make it unsuitable for direct contact. Alternative materials or an open knit design could improve comfort and functionality. Fusing temperature must be carefully controlled to avoid damaging the PVC tubing.

Images:

<table>
<tr><td>Sample#: 34</td><td>Tubing: 4</td></tr>
<tr><td>Yarns/threads: 4,9,14</td><td>Substrate: 3</td></tr>
<tr><td colspan="2">Method of integration: G</td></tr>
<tr><td colspan="2">Comments:
Low-melt nylon (14) was used as the bottom yarn in the coverstitch to test its adhesive potential for attaching a concealed tube to another substrate via heat treatment. The setup aimed for a coverstitch tail effect, creating a layered appearance. The fabric was constructed with the mesh facing up, and the tube was fed between the mesh and the dissolvable layer.
The bright white low-melt nylon combined with FE active merino wool improved handfeel and breathability. However, the knit is still too tight for skin contact; using every third needle could help. Low-melt nylon's fusible properties are essential, but a more open or zonal application could simplify manufacturing. The current multi-step method may require a more efficient alternative. Careful fusing temperature control is also critical to avoid tubing damage.</td></tr>
<tr><td colspan="2">Images:
 </td></tr>
</table>

Sample#: 35	**Tubing:** 10
Yarns/threads: 12,13,14,17	**Substrate:** 3
Method of integration: G	

Comments:

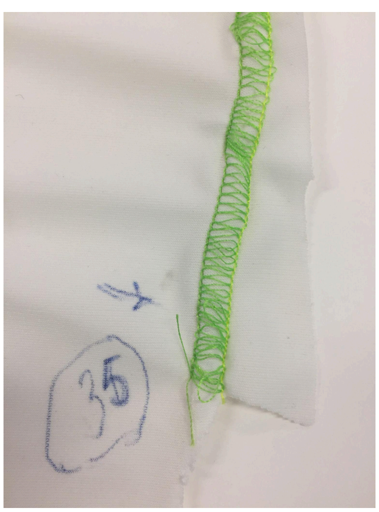
This swatch combines bright white low-melt nylon with FE active merino wool to encase tubing, zonally fused onto the stretch mesh. It offers improved handfeel and breathability compared to previous swatches, thanks to the merino wool. However, the knit remains too tight on the skin-facing side (could every third needle be used for more openings?).

Low-melt nylon is essential for its adhesive properties, but zonal application during the French braid process could reduce material use, albeit at the cost of increased manufacturing complexity. Translating this idea into a simpler, more manufacturable alternative might be more efficient (e.g., half the braid in a more open yarn and the other half in low-melt nylon).

For the coverstitch, low-melt nylon was tested as the bottom yarn, aiming to use it as an adhesive to attach the concealed tube via heat treatment. This could involve creating a coverstitch tail or cutting and mounting the fabric as a tail on a secondary fabric. While visually interesting, this multi-step process may not be efficient.

- The swatch improves handfeel and breathability.
- The knit is still too tight; using every third needle could create a more open structure.
- Zonal application of low-melt nylon during the French braid process could reduce material use but complicates manufacturing.
- A simpler alternative would streamline the process.
- Fusing temperatures must be controlled to avoid tubing damage.

Images:



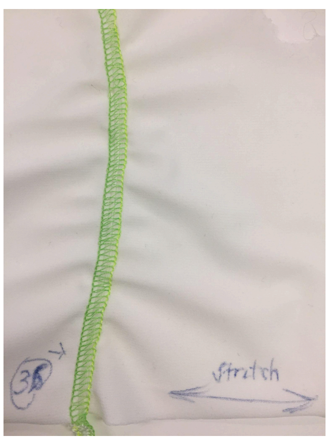
Sample#: 36	**Tubing:** 4
Yarns/threads: 12,13,14,17	**Substrate:** 3

Method of integration: G

Observations:
With the fabric stretched horizontally, I cover-stitched vertically, feeding the tube under the lime neon decorative stitch. Low-melt nylon (14) was used as the bottom yarn, running between the two parallel lines as an adhesive. The swatch is simple in appearance, with the colours not yet finalised.

- The adhesive may stick to the tubing, stabilising it but potentially affecting fluid dynamics due to stretching.
- This technique could be applied to existing garments, such as a black stretch mesh top, with a long, thin train cut and heat-pressed to shape, creating a fashionable warming garment.
- Further experimentation with colours and materials is needed for the desired aesthetic and functionality.
- Cutting frayed edges could add an interesting layered effect.

Images:

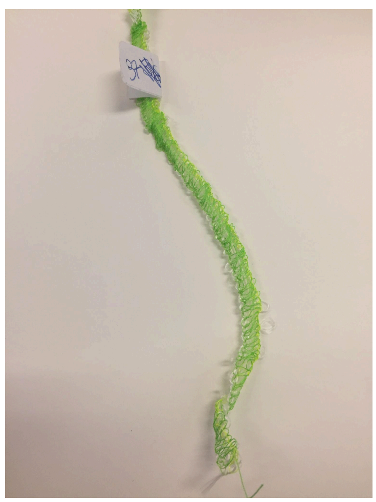


Sample#: 37	**Tubing:** 4
Yarns/threads: 12,13,14,17	**Substrate:** N/A
Method of integration: G	

Observations:
The swatch tail continues from the previous sample, omitting the substrate, with yarn (14) used as an adhesive for heat pressing onto another fabric layer. These swatches, made on spandex jersey, are more visually appealing, with a decorative stitch that appears delicate yet strong and improved colour choices.

- The loopy nature of yarn (14) and its twisting around the tube need refinement for functional and aesthetic consistency.
- Cutting frayed edges could create a layered effect, adding versatility when applied to a close-fitting top. This technique could also be used to add a long, thin train that is heat-pressed to shape, forming a fashionable warming garment.
- Further experimentation with colours and materials could enhance the design.

Images:

Sample#: 38	**Tubing:** 4
Yarns/threads: 12,13,14,17	**Substrate:** 3

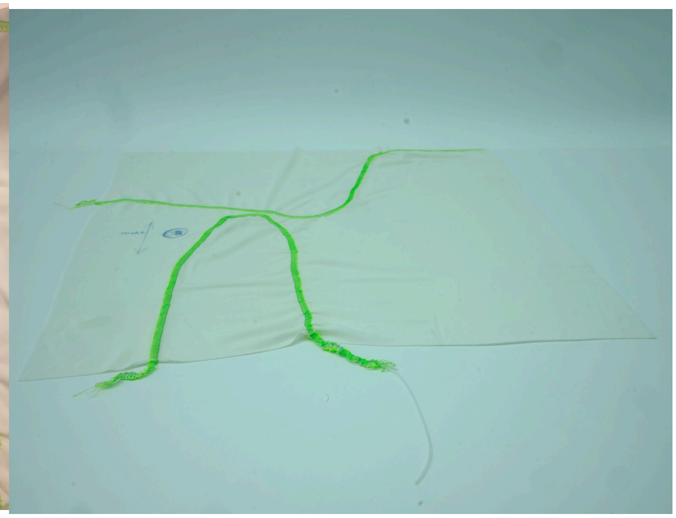
Method of integration: G

Comments:
This sample explores the directional placement of tubing and coverstitch to support fluid dynamics in stretchable fabric. Tubing and coverstitch were aligned with the fabric's stretch. If the tubing does not stretch and aligns with lines of non-extension, it will remain unstrained during movement or garment donning and doffing.

The swatch, made on spandex jersey, is visually appealing with a delicate yet strong decorative stitch and effective colour choices.

- Cutting frayed edges could create a layered effect, adding versatility when applied to garments, such as a long, thin train on a close-fitting top, enhancing style and warmth.
- Further refinement of colours and materials is needed to achieve the desired aesthetic and functionality.

Images:

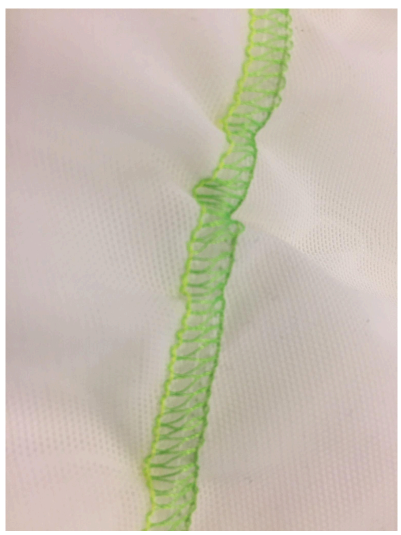


Sample#: 39	**Tubing:** 4
Yarns/threads: 12,13,14,17	**Substrate:** 1
Method of integration: G	

Comments:
This sample builds on the previous one, with the tube fed through the two lines of the coverstitch, but now uses spandex jersey as the substrate (1).
The switch to spandex jersey enhances the sample's visual appeal. The decorative stitch is both delicate and strong, with improved colour choices.

- Cutting frayed edges could create a layered effect, adding styling versatility. For example, this technique could be used on a close-fitting top, like a black one, to add a long, thin train that is cut and heat-pressed to shape, resulting in a fashionable and warming garment.
- Refinement of colours and materials is needed to optimise both aesthetic and functional qualities.

Images:

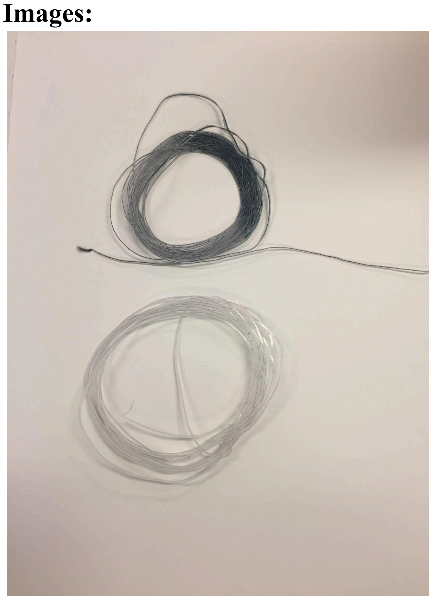




Sample#: 40	**Tubing:** N/A
Yarns/threads: 18&19	**Substrate:** 1
Method of integration: K	

Comments:
Two quick trials explored an alternative to tubing insertion based on the concept of channelling. The aim was to use yarn as an adhesive or to transition from soft to hard elements through heat treatment, creating breathable yet air- and watertight channels. Yarn was wound off cones and ironed for 10–30 seconds under Teflon.
The fusibility of the rubco yarns was tested, but the pressed texture became plasticky, making it unsuitable for direct skin contact, despite its visually appealing result.

- Explore less plasticky materials to ensure comfort and functionality while preserving aesthetics.
- Directly creating channels offers a promising alternative to tubing, but material selection is critical to achieving breathable, watertight properties.

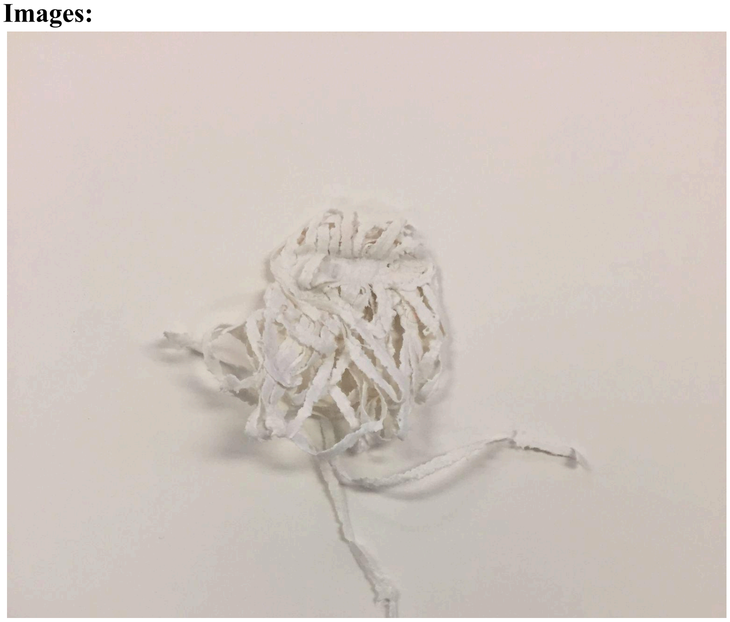
Images:



Sample#: 41	**Tubing:** N/A
Yarns/threads: 20	**Substrate:** 1
Method of integration: 1	

- Tested coiling PU yarn to evaluate its suitability for heat-pressing as an engineered fabric
- Aimed to create air- and water-tight yet breathable channels.
- The yarn was effectively welded under a flat section of the RF welder, demonstrating the concept's feasibility.
- Has a subtle and appealing texture, suggesting potential for interesting visual effects.
- Breathability of the welded material needs assessment to ensure comfort and functionality.
- Further exploration required to determine if this method can create channels that effectively replace traditional tubing while retaining the desired properties.

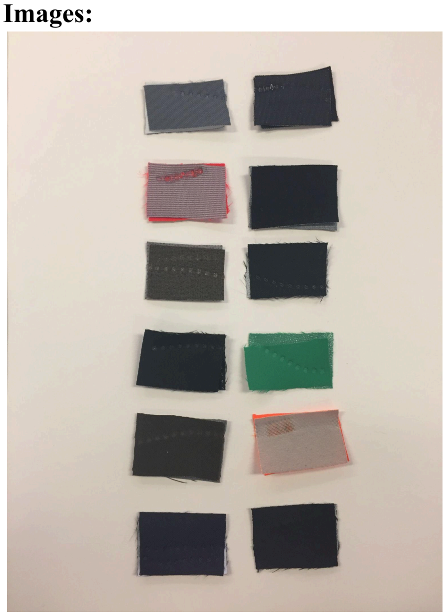
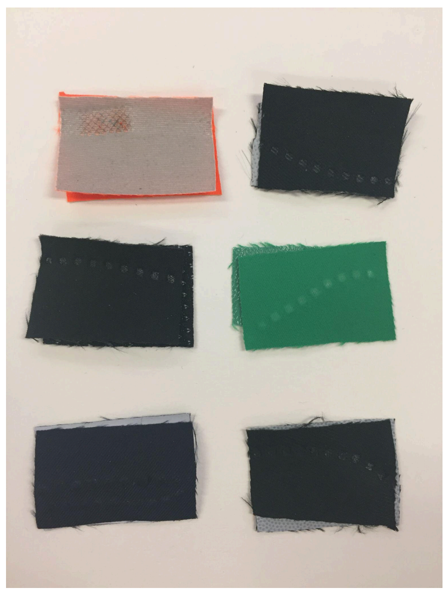
Images:



Sample#: 42	Tubing: N/A
Yarns/threads: 20	**Substrate:** 1
Method of integration: J	

Twelve breathable, waterproof fabric samples from activefabrics.co.uk were tested on an ultrasonic machine. While most welded successfully, only a few provided strong bonds and soft textures suitable for base layers. Welded seams offer distinct aesthetics and potential for varied finishes. However, concerns exist about seam strength, especially if channels house microfluidic tubing, as fit issues could compromise integrity. Further testing and careful material selection are critical to ensure durability and functionality. For woven fabric alternatives, development will take longer due to machine delays.

Images:

Appendix Q: CS2 Material sampling information - Knit

A series of knitted textile samples were developed using an 8-gauge hand flat knit machine at RCA and a CMS 822 machine (gauge 7.2) at STOLL, UK, supported by M1+ software. Created over five days in June and July 2020, the process combined specialist technical expertise, literature insights (Appendix V) and findings from parallel sampling (Appendix P).

The aim was to design wearable textiles with engineered channels for threading tubing (Appendix M), allowing gaps for skin contact. While tubing insertion required a manual post-process, knitting was deemed ideal for astronaut base layers due to its flexibility, conforming nature and potential for innovation.

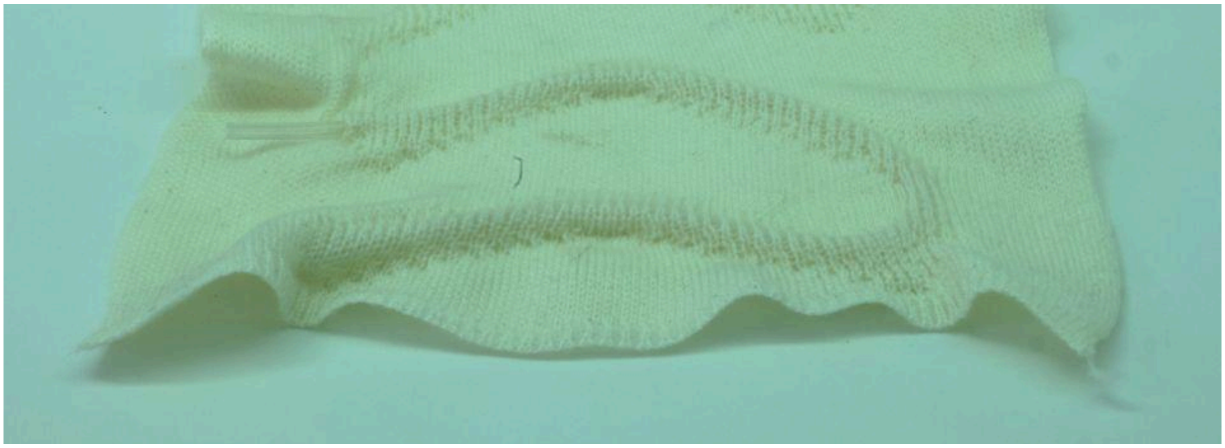
Techniques explored included plating, tubular knitting with monofilament binders, and interlocking. Key yarns (Appendix N.3) included 100% merino wool for its skin comfort, breathability, antimicrobial properties, and sustainability, alongside a viscose stretch yarn and polyester monofilament (Appendix N.3). Both single and double-faced weft knits were produced, with the single-faced fabric prioritised for an upper-body garment due to its lighter weight and material efficiency, critical for space applications.

Sample#: 5	**Tubing:**
Yarns/threads: c	**Substrate:** n/a
Method of integration: J	

Comments:

- Face and back of sample
- Single jersey structure, with integrated channels.
- Every other needle knitting at the back of the channel (the most closed of all the samples).

Images:



Sample#: 5a	**Tubing:**
Yarns/threads: c & b	**Substrate:** n/a
Method of integration: J	

Comments:

- Face and back of sample.
- Single-bed jersey with integrated channels.
- Every other needle knitted at the back of the channel.

Images:


Sample#: 6	**Tubing:**
Yarns/threads: 2	**Substrate:** n/a

Method of integration: J

Comments:

- Single jersey fabric.
- Interlocking stitch pattern.
- Alternating needles on one row and then on the other set.
- On the back side, knitting occurs on every 1 in 4 needles.

Images:

Sample#: 7	**Tubing:**
Yarns/threads: 2 &3	**Substrate:** n/a

Method of integration: J

Comments:

- Backside of sample.
- Double jersey, half Milano structure.
- The face uses yarn 3, while the back blends yarns 2&3.
- Knitting 1 in 4 at the channel.

Images:

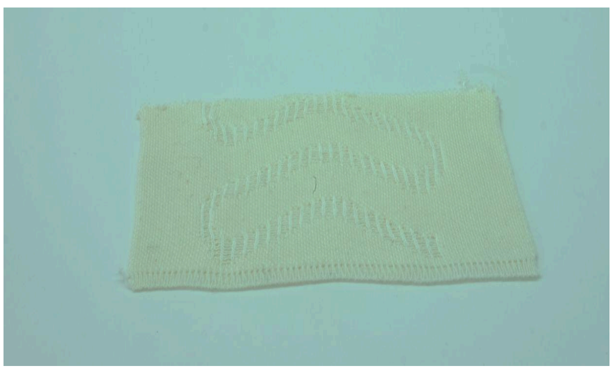
Sample#: 8	**Tubing:**
Yarns/threads: 2 &3	**Substrate:** n/a

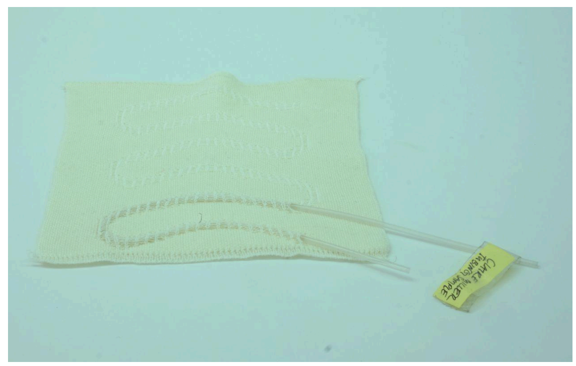
Method of integration: J

Comments:

- A double jersey, half milano, interlock (on the face side) structured fabric,
- All needles knitting on the front in a half Milano structure
- The area covering the back of the channel uses only Yarn 2, and every 1 in 4 needles knitting on the back.

Images:

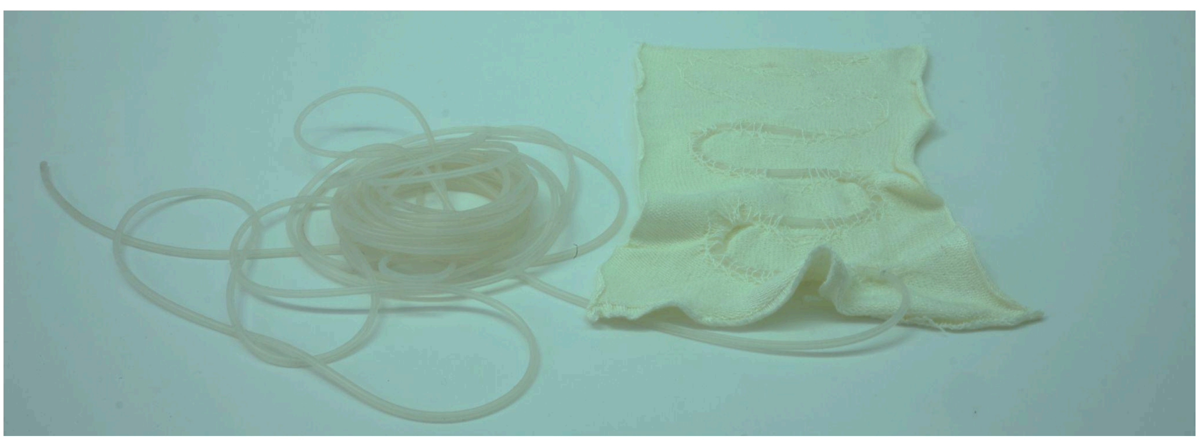




Sample#: 10	Tubing:
Yarns/threads: 2	**Substrate:** n/a
Method of integration: J	

- Face and back of unsteamed sample
- Single jersey and interlocked knitting throughout.
- On the back, every 1 in 6 needles knits within the channels, with vertically reduced stitches to minimise floats, resulting in wider gaps compared to previous
- The fabric has a soft, silky texture.
- The sample, after steaming to test shrinkage for tighter tubing fit, reduced in size from 36 cm to 26 cm.

Images:



Sample#: 11	**Tubing:**
Yarns/threads: 2 & 3	**Substrate:** n/a
Method of integration: J	

Comments:

After reviewing the first set of knitted samples documented above, the following samples were developed with a focus on increasing the openness at the back of the channel so that the contact between the tubing and the skin might be maximised and focus was placed on the development of single jersey knitted fabrics only to reduce yarn usage and thus sample weight. Additionally, the samples were developed using a combination of both yarn 2 and 3

- Single jersey interlock all over in yarns 2 & 3.
- Floats that hold the tubing in place on the backside are every one in six stitches.
- It has a lovely hand, although perhaps too heavy weight for an application in space would likely be suitable for another terrestrial application.

Images:


Sample#: 12	**Tubing:**
Yarns/threads: 2&3	**Substrate:** n/a
Method of integration: J	

Comments:

- Blend of yarns 2&3.
- Uses the plating technique with the merino yarn on the face side.
- knitted every one in six stitches on back of channel.

Images:

Sample#: 13	Tubing:
Yarns/threads: 2&3	**Substrate:** n/a

Method of integration: J

Comments:

- Back and face of an iteration of the previous sample.
- Single jersey interlock
- The stitches on the back are holding every one in five needles.

Images:


Sample#: 14	**Tubing:**
Yarns/threads: 2&3	**Substrate:** n/a
Method of integration: J	

Comments:

- Interlocking stitches.
- Similarly to the previous sample, the stitches on the back are holding every 1-5 knitted needles, but with half the amount of floats (so it is a bit more open on the back)..
- It is a sturdy fabric that feels too thick for the desired application.

Images:

Sample#: 15	**Tubing:**
Yarns/threads: Blend of 2&3	**Substrate:** n/a

Method of integration: J

Comments:

- Face and back
- Interlocking stitches
- Picking up every one in every five stitches with half the amount of floats.

Images:

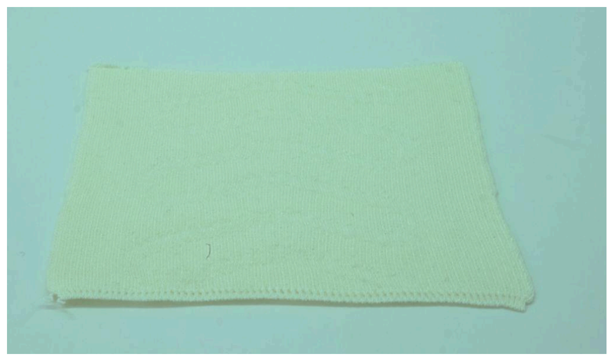
Sample#: 17a	**Tubing:**
Yarns/threads: 1&2	**Substrate:** n/a

Method of integration: J

Comments:

- Tubular knit structure with yarn one acting as a binding yarn.
- This technique produces a much thicker fabric.
- In the channels, the back picks up every 1 in 5 stitches, halving the floats

Images:

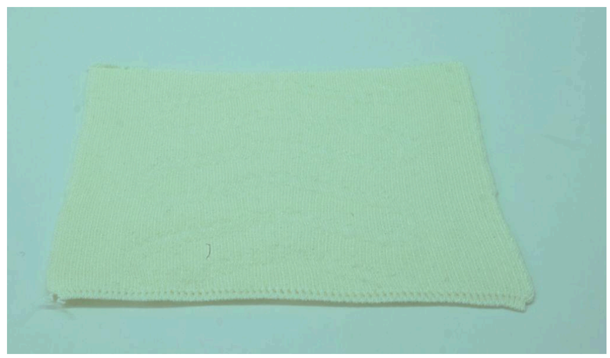


Sample#: 17b	**Tubing:**
Yarns/threads: 1&3	**Substrate:** n/a
Method of integration: J	

Comments:

- Tubular knit structure with yarn one acting as a binding yarn.
- In the channels, the back picks up every 1 in 5 stitches, halving the floats.
- This technique produces a much thicker fabric.
- Without the stretch yarn this sample is larger in size than 17a.

Images:



Sample#: 17c	**Tubing:**
Yarns/threads: 1&3	**Substrate:** n/a

Method of integration: J

Comments:

- Face and back side
- In the channels, the back picks up every 1 in 5 stitches, halving the floats.
- Tubular knit structure with yarn one acting as a binding yarn.
- This technique produces a much thicker fabric and is larger in size than those that use yarn 2

Images:

Appendix R: Designing the garment prototype

Ferl and others.[420] have indicated that it is possible to minimise the total amount of tubing in a thermoregulation garment to increase mobility and dexterity by increasing cooling in areas of the body such as the torso, neck and head – regions particularly effective at thermoregulation – while reducing tubing in less critical areas, such as the arms. However, the pattern developed in this study includes arm panels to provide the necessary surface area for connecting the tubing to the wrist-worn thermoregulation device. The pattern was designed by Emma Hamshare, an MA graduate in Textile Design from the Royal College of Art, who adapted it from a design being developed for an exo-suit garment as part of the FAIR-SPACE project (See Appendix L).

Tubing tracks were integrated into the upper-body garment pattern and knitted textile design, with the tubing fed through the channels in a secondary, hands-on process. The tubing layout pattern was informed by discussions with a scientific project contributor and examples in literature (see 5.3.1.5). The design is considered demonstrative and would require further optimisation. A single jersey fabric was selected after the sampling process due to its lower weight and cost than double-jersey fabrics, which, despite offering higher yarn coverage, were deemed less viable.

The garment prototype was designed specifically to integrate the wrist-worn thermoregulation device. While design iterations based on feedback from scientific project contributors would be crucial for further development, this phase of the research was conducted independently. We did collaborate on an successful initial liquid pump test to assess whether water could flow effectively throughout the garment which I had prepared by embedding tubing into the pre-designed channels. The results of this test are demonstrated in (5.3.1.1). Red ink was added to the liquid as a marker and liquid flowed freely through the flexible polymeric tubing. Further testing of the design's thermoregulatory efficiency was not conducted and the research remains in the preliminary stages.

Figure R.1. *The garment prototype.*

[420] Ferl and others, 'Trade Study of an Exploration Cooling Garment'.

Appendix S. Literature Review: Challenges and opportunities of liquid cooling ventilation garments in space

S.1. Introduction to Liquid Cooling Ventilation Garments (LCVGs)

The Liquid Cooling and Ventilation Garment (LCVG), also known in some contexts as the Liquid Cooling Garment (LCG), plays a critical role in managing astronaut body temperature during extravehicular activities (EVAs), such as space-walks. While the LCG focuses on cooling by circulating chilled liquid through a network of tubing, the LCVG enhances this functionality by also incorporating ventilation to remove sweat and water vapour, helping to maintain thermal comfort and dryness. The LCVG consists of approximately 91.5 metres (300 feet) of polymeric tubing that circulates water to absorb excess heat and maintain optimal conditions inside the space-suit.[421]

Despite being developed more than fifty years ago for the Apollo missions, the LCVG remains largely unchanged.[422] It remains the most effective wearable cooling solution,[423] thanks to its durability and reliability, forming the foundational layer of the Extravehicular Mobility Unit (EMU), which comprises 21 layers. A comprehensive review of water-cooled garments (WCG) and LCG/LCVGs can be found in Nunneley's review.[424]

S.2. Tubing within the LCG/LCVG: Structure and material considerations

The tubing used within the LCG/ LCVG is designed to conduct heat away from the body by being in direct contact with the skin. This necessitates a form-fitting base layer garment to ensure effective heat transfer. Compatibility between tubing and skin needs to be considered. This includes factors such as the stability of the polymer against breakdown from internal liquids and perspiration and the polymer's ability to prevent fungal growth.[425] The elastomeric nature of the tubing, made from materials such as polyvinyl chloride (PVC), ethylene-vinyl acetate (EVA) or silicone, supports the donning and doffing of the garment and accommodates the motion of the wearer.

Challenges such as the tubing kinking and the loss of contact surface area with the skin can affect cooling performance. Tubing characteristics can also impact by affecting their incorporation into textiles and heat transfer capability.[426] For example, while a smaller tubing size would enable greater compatibility with textile processes and provide a more integrated and flexible solution, it becomes harder to pump the liquid without risking technical failure. Ferl et al.[427] indicate that as the ratio between the wall

[421] 'Solving Space - Cooling Garments', Space Center Houston.
[422] Daniels, 'Thermal Performance Analysis of the Liquid Cooling and Ventilation Garment (LCVG) with Respect to Tubing Geometry', p. 4.
[423] Amjed and Ali, 'Liquid Cooling Garment Configuration and Investigation'; Gernhardt and others, *Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems*, MMVIII.
[424] Sarah A. Nunneley, 'Water Cooled Garments: A Review', *Space Life Sciences*, 2.3 (1970), pp. 335–60, doi:10.1007/BF00929293.
[425] Leith and Hixon, *Development and Fabrication of an Advanced Liquid Cooling Garment*, p. 8.
[426] Daniels, 'Thermal Performance Analysis of the Liquid Cooling and Ventilation Garment (LCVG) with Respect to Tubing Geometry'.
[427] Ferl and others, 'Trade Study of an Exploration Cooling Garment'.

thickness and the tubing diameter decreases, the burst strength also decreases, with a greater tendency for the tubing to kink and create gaps in the contact surface area. To address these issues, LCVGs/LCGs typically use tubing with a 3/16-inch to 1/4-inch outer diameter (OD) and 1/32-inch to 3/16-inch inner diameter (ID)[428] to balance flexibility with cooling capabilities. The tubing geometry used in the current EMU LCVG has a circular cross-section with a 1/8-inch OD, a 1/16-inch ID, and a wall thickness of 1/32 inches.[429]

S.3. Challenges and Opportunities of Current LCVG Designs

While the LCVG is effective, there are a number of complexities inherent in current designs, as articulated by America's National Aeronautics and Space Administration (NASA) and its collaborators,[430] who identified the potential for enhancement through the simplification of their 'bulky and overly complex' designs.[431] As space missions become longer and more frequent, the need for more efficient extravehicular activity (EVA) equipment (including the LCG/LCVG) grows, demanding advancements in the life-sustaining technologies originally designed for shorter, less frequent missions.[432]

Recent improvements to the LCG/LCVG have primarily focused on reducing the size and weight of auxiliary components,[433] such as adjusting the cooling liquid inlet temperatures,[434] revising the tubing's distribution layout and modifying the tubing geometry.[435]Despite the significant impact that a garment's sensory and aesthetic attributes can have on perceptions of comfort and fit,[436]factors critical to thermoregulation yet underexplored in current solutions,[437]the current fabric remains an off-the-shelf nylon/lycra warp knit construction. While these materials offer stretch and breathability and allow tubing to be woven through the mesh (as seen in Figure 4), they are also thermal insulators, limiting effective heat transfer.[438]

Issues related to the comfort and fit of the LCG/LCVG can directly impact their thermal performance. Section 5.3 discussed how a combination of relatively stiff tubing and a finer fabric weight can cause the fabric and tubing to buckle away from the body during motion (refer to Figure 5.4b). Without good contact between the garment and the skin, thermoregulation is either reduced or not possible in certain areas, ultimately affecting the overall thermal performance.[439] Impaired cooling capability can affect both cognitive and physical performance. Hard elements of the suit can rub against

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[428] Ferl and others, 'Trade Study of an Exploration Cooling Garment'.
[429] Conger and Makinen, 'High Performance Torso Cooling Garment'.
[430] Ferl and others, 'Trade Study of an Exploration Cooling Garment'.
[431] Trevino and others, 'Flexible Fabrics with High Thermal Conductivity for Advanced Spacesuits'.
[432] Gernhardt and others, *Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems*, mmviii.
[433] Khan and others, 'Physiological Adaptations in Space and Wearable Technology for Biosignal Monitoring', p. 45.
[434] Bue and others, 'Experimentally Determined Overall Heat Transfer Coefficients for Spacesuit Liquid Cooled Garments'.
[435] Conger and Makinen, 'High Performance Torso Cooling Garment'.
[436] Matté, Broega, and Pinto, 'When Clothing Comfort Meets Aesthetics'; Das and Alagirusamy, 'Neurophysiological Processes in Clothing Comfort'.
[437] Compton, 'Fit for Space: Leveraging a Novel Skin Contact Measurement Technique toward a More Efficient Liquid Cooled Garment'.
[438] Trevino and others, 'Flexible Fabrics with High Thermal Conductivity for Advanced Spacesuits'.
[439] Compton, 'Fit for Space: Leveraging a Novel Skin Contact Measurement Technique toward a More Efficient Liquid Cooled Garment'.

the skin, causing discomfort, which not only affects physiological wellbeing but also psychological comfort, the perception of which is highly subjective, with its effects not yet fully understood. Furthermore, the logistical burden of auxiliary equipment,[440] required as part of the LCG/LCVG assembly, could be minimised through engineered textile design that integrates components such as shoulder padding, an optional thermal undergarment[441] and the tubing itself into a single textile system.

S.4. Opportunities for Improvement and Future Design Prospects

As space travel expands – it is anticipated to be undertaken by both astronauts and commercial space travellers – there is a growing need for scalable and cost-effective production methods. There will also be inevitable technology transfer from specialised aerospace applications to terrestrial applications requiring wearable cooling systems.[442]

Thus, there is an unfolding opportunity for textile designers to apply their expertise in the context of the design and manufacture of thermoregulation garments which offer attractive, marketable and scalable solutions. Improving the efficacy of personal cooling systems, through a variety of means, is fundamental to space missions. Since the fundamental challenge of sustaining life within these extreme conditions of space has been met by skill-sets found within science-led domains, there is now also scope to include a wider range of approaches and methods, such as the integration of psychological and sensorial comfort with thermo-physiological comfort.[443] A unique opportunity exists for the creative contribution of 'softness' through applied textile design research. With further funding, a wider range of approaches could be explored, including customisation and personalisation using advanced textile techniques which could lead to the improved overall comfort essential for the well-being of astronauts during prolonged space

[440] Ferl and others, 'Trade Study of an Exploration Cooling Garment'.
[441] Ibid.
[442] Leith and Hixon, *Development and Fabrication of an Advanced Liquid Cooling Garment*.
[443] Das and Alagirusamy, *Science in Clothing Comfort*.

Appendix T: CS2 Textile design roles, methods, activities and their associated learning modes

Table T.1. *CS2 Textile design roles, methods, activities and their associated learning modes*

Role in the project	Key method employed	Activities	Outcomes	Learning mode
Desk-based researcher	Literature review	Review literature related to thermoregulatory textiles and current solutions employed in astronaut thermoregulation.	Increased understanding of the challenges faced in the domain and a direction for sampling informed by literature	Reading and writing; explicit knowledge 'know-what'.
Embedded researcher	Familiarisation and semi-structured interviews	- Familiarisation of research setting, culture, materials and challenges being faced enabled by embedding myself physically within the HCRS—sharing experiences to facilitate knowledge building; initial 'show-and-tell' meetings and key relationships that have supported and maintained the relationships. - Interviewing those involved in the FAIR-SPACE project from ICL and RCA.	- Understanding of where textile design expertise would be most usefully employed and which aspects of my skill set are of value (or not); - Developed insights and understanding of critical perspectives and experiences beyond my own to support an analysis of the research study.	-Embodied and experiential knowledge; 'Know-how'. - Relational 'Know-with'.
Maker	Embroidery and knitting	- Organising and booking machinery; - Organising and procuring yarn selection; - Communicating between disciplines and subject matter expertise.	A range of embroidered and knitted samples demonstrating exploration of integrating flexible polymeric tubing into textiles through a range of techniques; Knowledge transfer.	- Kinaesthetic; - tacit experiential and explicit 'know-how' and 'know-what'.

Appendix U: COC TDS

TECHNICAL DATA SHEET

TOPAS Advanced Polymers

TOPAS® ELASTOMER E-140

Cyclic Olefin Copolymer (COC)

Thermoplastic Polyolefin Elastomer with good transparency, excellent barrier properties and high purity.

Property	Value	Unit	Test Standard
Physical Properties			
Density	940	kg/m³	ISO 1183
Melt volume rate (MVR) @ 260°C/2,16kg	12	cm³/10min	ISO 1133
Melt volume rate (MVR) @ 190°C/2,16kg	3	cm³/10min	ISO 1133
Mechanical Properties			
Tensile modulus (1mm/min)	50	MPa	ISO 527-2/1A
Tensile stress at break (50mm/min)	46	MPa	ISO 527-2/1A
Tensile strain at break (50mm/min)	> 500	%	ISO 527-2/1A
Tensile modulus (1mm/min) @ -50°C	1700,0	MPa	ISO 527-2/1A
Tensile stress at break (50mm/min) @ -50°C	26	MPa	ISO 527-2/1A
Tensile strain at break (50mm/min) @ -50°C	> 200	%	ISO 527-2/1A
Tear strength	47	kN/m	ISO 34-1
Compression set - @72h / 23°C	32	%	ISO 815
Compression set - @24h / 60°C	90	%	ISO 815
Hardness, Shore A	89	-	ISO 868
Thermal Properties			
Tm - Melt temperature (10°C/min)	84	°C	ISO 11357
Vicat softening temperature A50 (50°C/h 10N)	64	°C	ISO 306
Barrier Properties			
Water vapor permeability @ 23°C, 85% RH	1,0	g×100µm / m2×day	ISO 15106-3
Water vapor permeability @ 38°C, 90% RH	4,6	g×100µm / m2×day	ISO 15106-3
Oxygen permeability @ 23°C, 50% RH	1200	cm³ ×100µm / m2×day×bar	ASTM D3985

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Appendix V: CS2 Project contextual background

My position as 'Researcher in Residence' on the FAIR-SPACE project at the HCRS, ICL was made possible by a developing partnership between the RCA's Textile Design Department and the HCRS, ICL in association with ICL's Department of Computing (Faculty of Engineering) and Department of Surgery and Cancer (Faculty of Medicine). The FAIR-SPACE project is funded by a major grant from the Engineering and Physical Sciences Research Council (EPSRC), [EP/R026092/1][444]

The FAIR-SPACE hub (Figure V1.a) aims to advance Robotics and Artificial Intelligence (RAI) 'for future utilisation and exploration' to position the UK as a leader in the field. It addresses the UK's national priorities in space, including orbital manipulation, autonomous planetary vehicles and robotic support for manned exploration.[445] ICL is one of six universities working in the FAIR-SPACE hub (Figure 1c), supported by several national and international companies, representing major space agencies, research institutions and cross-sectional RAI organisations.

Researchers at HCRS, ICL focusing on the hub's fourth thematic area, 'human-robot interaction' (Figure V.1b), with a focus on the spacesuit, anticipated that support from the RCA Textile Design department could enhance the design and development of 'wearable' technology systems. The work aimed to enhance technological systems and integrate them into wearable technology garments or the innersuit structure. This work included exploring suitable textile structures and methods, such as knitting, weaving, printing and embroidery/stitching. As an embedded textile design researcher, I addressed the challenge of thermoregulation (Figure V.1d). I engaged with an electronics engineer specialising in medical devices to develop textile samples with integrated polymeric tubing (see 5.2.) and with a medical robotics engineer, specialising in MRI-guided endovascular interventions on the early-stage development of a 'fibre' with integrated heating and cooling capability (Appendix J).

The broader partnership between HCRS, ICL and RCA's Textile Design department included three additional strands:

1. An eight week project titled 'The Future Traveller', where elective MA RCA Textile Design students creatively addressed three technology challenges outlined by the 'FAIR-SPACE' HCRS ICL research team: thermoregulation, self-cleaning coatings and soft-hard responsive surfaces.
2. Two graduate MA RCA Textile Design Research Assistant positions at Imperial College working on the design and development of an exo-suit to support strengthening joint

[444] EPSRC, 'Future AI and Robotics Hub for Space (FAIR-SPACE)', *Grants on the Web, Engineering and Physical Sciences Research Council* (Engineering and Physical Sciences Research Council, Polaris House, North Star Avenue, Swindon, SN2 1ET) <https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R026092/1> [accessed 3 August 2024].
[445] FAIR-SPACE HUB, *FAIR-SPACE Annual Review*, 2020 <https://static1.squarespace.com/static/5a6a02b0f6576ed25151ecfa/t/601431bfcee52a5ae3718bc7/1611936246186/Fair_Space_AR_2020.pdf> [accessed 8 April 2021].

mobility building on existing technological developments[446] yet to be integrated into a more wearable system;

3. RCA Textile Design staff and researchers working to integrate a complex bio-sensing system into a wearable item using textile methods.

Figure V. 1. *a) FAIR-SPACE, National Hub of Research Excellence on Future AI and Robotics for Space. Image credit: FAIR-SPACE Annual Review 2020. b) Overview of the FAIR-SPACE hub's five thematic focus areas. Image credit: FAIR-SPACE Annual Review 2020. c) Overview of FAIR-SPACE participating governmental funding bodies and university partners. Image credit: FAIRSPACE Annual Review 2020. d) Profile page of ICL participating researchers. Image credit: FAIRSPACE Annual Review 2020.*

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[446] Rejin John Varghese, Benny Ping Lai Lo, and Guang-Zhong Yang, 'Design and Prototyping of a Bio-Inspired Kinematic Sensing Suit for the Shoulder Joint: Precursor to a Multi-DoF Shoulder Exosuit', *IEEE Robotics and Automation Letters*, 5.2 (2020), pp. 540–47, doi:10.1109/LRA.2019.2963636.

Appendix W: CS2 Ethics forms

Imperial College London

Bioengineering Department
Imperial College London

Royal School of Mines
South Kensington Campus
SW7 2AZ
Tel: +44 (0)7950 972033

e.burdet@imperial.ac.uk
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Professor Etienne Burdet
Chair in Human Robotics

23 April 2020

To the RCA ethics committee,

Please find this letter to be an expression of approval for Claire Felicity Miller to recruit participants from her team on the FAIRSPACE research project at Imperial College and to utilise data supplied by them within her PhD research that she is undertaking at the Royal College of Art in Textile Design.

Yours sincerely,

Etienne Burdet

Imperial College of Science, Technology and Medicine

RCA Ethics (sent by sophie.matthews@rca.ac.uk)
to Elif, Sara, Elaine, me

Mon, 27 Apr, 15:57 (11 days ago)

Dear Claire,

You ethics assessment has been approved.

Kind regards,

The Research Ethics Team

Royal College of Art
RESEARCH & INNOVATION

Participant Project Information & Consent Form

(One signed copy of this form should be retained by the Participant and one copy by the Project Researcher)

Soft: A textile design approach to crafting smart textiles at the edges of the discipline

For further information
Supervisor:
Elif Ozden-Yenigun
Elif.ozden-yenigun@rca.ac.uk

28 May 2020

Dear Rejin,

I am a PhD research student in the Textile Design Department at the Royal College of Art. As part of my studies I am conducting a research project entitled, '*Soft: A textile design approach to crafting smart textiles at the edges of the discipline*' and the project is externally sponsored by *The Stavros Niarchos Foundation*. You are invited to take part in this research project which explores interdisciplinary textile design practices in the emerging fields of smart textile design research and practice. Through analysis of this emerging interdisciplinary design space—come about as textile design increasingly intersects with the Sciences—I hope to contribute towards a better understanding of contemporary textile design processes and practices.

If you consent to participate, this will involve:
A recorded interview that may be included (or elements thereof) in the thesis.

Participation is entirely voluntary. You can withdraw at any time up to the point of publication and there will be no disadvantage if you decide not to complete the study. All information collected will be confidential. All information gathered will be stored securely and once the information has been analysed all individual information will be destroyed.

Research Office Royal College of Art Kensington Gore London SW7 2EU
t +44 (0)20 7590 4126 f +44 (0)20 7590 4542 research@rca.ac.uk www.rca.ac.uk/research

(a) At no time will any individual be identified in any reports resulting from this study.

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Elif Ozden-Yenigun at the above address.

Thank you for your interest.

I, *Rejin John Varghese*, have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature Rejin John Varghese

Researcher Signature……

Date: …………29/05/2020………………………………………………

Complaints Procedure:

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

The Research Ethics Committee
Royal College of Art
Kensington Gore
London
SW7 2EU

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Elif Ozden-Yenigun at the above address.

Thank you for your interest.

I *(please print)* STEPHANIE PAH have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature……………………………

Researcher Signature…… Claire Miller ……

Date: 29/5/2020

Complaints Procedure:

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

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If you have any concerns or would like to know the outcome of this project, please contact my supervisor Elif Ozden-Yenigun at the above address.

Thank you for your interest.

I, *Panagiotis Kassanos,* have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature…Panagiotis Kassanos……………………………………………………

Researcher Signature ………………………………

Date: …21/05/2020…………………………………………………………………………

<u>Complaints Procedure:</u>

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

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Kensington Gore
London
SW7 2EU

I *(please print) ELIF OZDEN YENIGUN* have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature…………

Researcher Signature

Date: ……………………………04.08.2020…………………………………………

Complaints Procedure:

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

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Royal College of Art
Kensington Gore
London
SW7 2EU

destroyed. (a) At no time will any individual be identified in any reports resulting from this study.

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Elif Ozden-Yenigun at the above address.

Thank you for your interest.

I *(please print)* ..Emma Hamshare....... have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature..

Researcher Signature.......Claire Miller...

Date: 02.06.2020 ....

Complaints Procedure:

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

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Royal College of Art
Kensington Gore
London
SW7 2EU

Thank you for your interest.

I *(please print)* ...*Johanna Alisha Pinto*.... have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant

Signature...

Researcher Signature..........Claire Miller...

Date: ...4/06/2020...

<u>Complaints Procedure:</u>

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

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Royal College of Art
Kensington Gore
London
SW7 2EU

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Elif Ozden-Yenigun at the above address.

Thank you for your interest.

I *(please print)* …*Anne Toomey*……………………………….. have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature……

Researcher Signature…

Date: ……27th July 2020………………………………………………………………

Complaints Procedure:

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

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Royal College of Art
Kensington Gore
London
SW7 2EU

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Elif Ozden-Yenigun at the above address.

Thank you for your interest.

I Amy Winters have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature 

Researcher Signature 

Date: 05/08/20

Complaints Procedure:

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

The Research Ethics Committee
Royal College of Art
Kensington Gore
London
SW7 2EU

If you have any concerns or would like to know the outcome of this project, please contact my supervisor Elif Ozden-Yenigun at the above address.

Thank you for your interest.

I *(please print) …Mohamed Abdelaziz*……………………………… have read the information above and all queries have been answered to my satisfaction. I agree to voluntarily participate in this research and give my consent freely. I understand that I can withdraw my participation from the project up to the point of publication, without penalty, and do not have to give any reason for withdrawing.

I understand that all information gathered will be stored securely, and my opinions will be accurately represented. Any data in which I can be clearly identified will be used in the public domain only with my consent.

Participant Signature……Mohamed Abdelaziz…………………………………………………………….

Researcher Signature

Date: 12/06/2020

<u>Complaints Procedure:</u>

This project follows the guidelines laid out by the Royal College of Art Research Ethics Policy.

If you have any questions, please speak with the researcher. If you have any concerns or a complaint about the manner in which this research is conducted, please contact the RCA Research Ethics Committee by emailing ethics@rca.ac.uk or by sending a letter addressed to:

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Appendix X: Researcher in residence proposal

CLAIRE FELICITY MILLER
Proposed start date: 28 October 2019

The aim of the researcher in residence will be to explore suitable textile structures and viable methods either knitting, weaving, print or embroidery for integrating the complex bio-sensing system developed by the FairSpace team into a wearable layer or as part of the inner-suit structure. We envisage that this will require multiple textile processes, testing materials, prototyping and working together with the key researchers within the FairSpace team to find potential methods for integrating the technology successfully. We propose that the researcher would be embedded within the team at Imperial for 6 months (with potentially another 6 month extension) with access to key facilities at the RCA over that period.

The core facilities at the RCA that we will be utilising are the knitting workshops, and digital knitting machines (Shima Seiki), the mixed-media workshop embroidery machines, yarn twister, and potentially print and weave facilities. The workshops offer the variety and breadth of equipment for prototyping a variety of approaches to the challenge of integrating sensing systems into textile structures starting from designing yarn to final cloth. There may also be a requirement depending on the direction of the prototyping to outsource the use of specialist equipment to develop more resolved final prototypes. We have identified potential facilities in digital knit in the UK and also identified potentially relevant academic collaborators.

Researcher profile
In order to progress and support the design and development of the proposed intra-vehicular bio-sensing suit we propose that Claire Miller works in residence at the Hamlyn Centre for a period of 6 months under the supervision of Dr Sara Robertson and Dr Elif Ozden-Yenigun.

Claire Felicity Miller is a textile designer and researcher currently entering the 3rd year of her PhD at the RCA where she is also a visiting lecturer on the MA Textile Design programme. Claire's PhD research is focused on smart textile design as an emerging discipline and the skills and knowledge required for textile designers to work within this developing field. Collaboration as a method to reveal new knowledge is a key part of her PhD enquiry. Claire aims to use this experience as a case study within her PhD (aiming to complete in January 2021). Prior to joining the RCA Claire worked as a material designer for Nike's innovation design team on elite level athlete performance footwear. Recent and relevant experience as part of her PhD includes using the textile design facilities at the RCA to integrate polymer optical fibre (as sensors) into knitted textile structures (Figures 1 and 2), testing machine compatibility to embroider with a range of conductive yarns (Figure 3 and 4) and silk screen printing onto textile substrates with metallic and nano-based conductive inks (Figures 5 and 6). Claire's focus within the FairSpace team would be the translation of challenging materials and integration of technology into wearable textile structures.

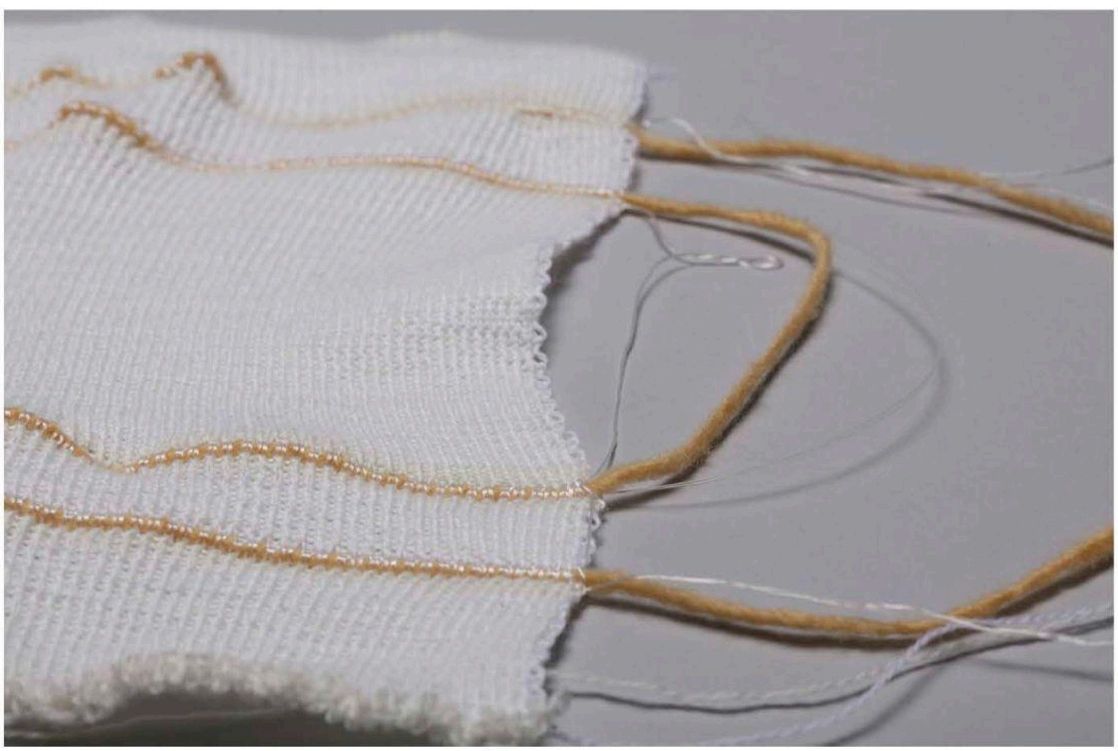


Figure 1 & 2, Knitted textile samples with integrated polymer optical fibres, merino wool and high wicking yarn (2019).

Figures 1 & 2 show knitted textile prototypes in which polymer optical fibre has been fed through the knitted loops of the textile (alongside a thicker yarn to prevent movement within the structure) in a process called 'inlaying'. Inlaying was identified through prototyping and a literature review as a method that would put minimal strain on the POF as well as maintaining the conformability/stretch desired when working with knitted textiles. The knitting machine used was a Shima Seiki SRY183LP-SC, Gauge 10, using a computer system and software SDS-ONE, Apex 3.3 — Knit Paint (R15). The fabric developments were conducted using 0.25 mm unsheathed polymer optical fibres made from PMMA (Poly Methyl Methacrylate) supplied by Universal Fibre Optics and manufactured by Mitsubishi in combination with various other yarns. The additional yarns were selected for their thermal regulation properties and handle. This method of inlaying sensors through knitted textile construction could support the FairSpace project through allowing the integration of electronic components and circuitry within a soft base.


RED
BLACK
brother
6 5 4 3 2 1

Figure 3 & 4, Embroidered samples (2018)

Figures 3 & 4 show an exploration of embroidery machine compatibility for the use of a variety of commercially available conductive yarns (including silver yarns and anti-static stainless steel fibres). The machines used at RCA were a Brother PR 600 and a ZSK Racer 1W and the software used was Ethos-aps. The yarn used in these images is a silver plated nylon 66 235/34 dtex s300 HC available from Shieldex. This specialist textile process could allow freedom of design options (not restricted by linear construction) for us to connect and create required transmission lines without interfering with the structural integrity of the cloth.

Figure 4 & 5, Silk screen printed graphene based antennas on cotton fabric (2019).

Figure 4 & 5 show silk screen printed antennas produced at the RCA using graphene oxide conductive ink, supplied and manufactured by DZP technologies, on cotton. These samples were produced as part of a larger investigation into the fabrication of soft textile antennas and this particular focus of the study explored silk screen printing a range of metallic and nano-based inks on a variety of base fabrics. The results were then tested by a collaborator and compared against other inks and textile construction methods for efficiency as flexible, textile antennas. Silk screen printing processes work as a stencil where ordinarily, the screen is coated with a photo-sensitive emulsion and then dried before the artwork (in this case the antenna design) is exposed as a positive in an exposure unit before printing with the desired materials. Thus, it enables us to decorate the surface with functionalized materials to work efficiently with other components and finally complement them.

These examples demonstrate some of the textile design processes that Claire has experience with and could be used in the prototyping of the inner-suit for bio-sensing. These three-ways of making when combined, could support the following design challenges (i) hard-soft combination for integration of actuators and electronic components (ii) assisting thermal regulation through hidden textile based solutions either by patterning or the integration of cooling tubes and (iii) employing smart and functional materials that can bring soft play while complementing electronic components.

Proposed outline of residency

In terms of how we imagine the residency working, Claire would be embedded in the Fair Space team for the duration of the residency. This would involve Claire having a desk/working space at Imperial if possible. Claire would still retain her supervision at the RCA and be able to access the expertise of the Textiles Team and use the facilities for prototyping. We hope that Claire could join you as part of the team as soon as possible and work with you until May 2020. Claire could work on specific elements of prototyping for the inner-suit design but also she would be well suited to working across other challenge areas. Part of the residency for Claire is to gain insight and understanding of the value of knowledge and skills of a textile designer working across disciplines between design and science. She would work closely with FAIRSPACE team to provide effective and tuneable textile solutions by using a broad range of textile making within the aim of increasing the technology readiness level of prototypes. We imagine that Claire will bring value not only in terms of design solutions but also through different ways of thinking and approaching the application of new technology for a Space environment.

Time plan for 6 month residency	
28th Oct — 28th Nov	• Introducing research and understanding shared research aims and objectives; • Familiarisation of technical challenges presented by the developed technology and restrictions that would impact on successful integration into soft materials; • Sharing of existing research and challenges presented within the space environment; • Refining a brief for the residency based on shared vision and feasibility; • Literature review and material sourcing
28th Nov — 28th Dec	• Literature review and material sourcing; • Establishing compatibility between materials and machinery to support developed brief; • Low fi prototyping to establish design potential and feasibility
28th Dec — 28th Jan	• Literature review and material sourcing; • Prototyping development, analysing successful samples, testing and re-iteration; • Documenting process and results • Design review with team
28th Jan — 28th Feb	• Refinement and further development of prototypes; • Testing and analysis of results; • Review progress and establish plan and construction methods, materials and access to equipment for final designs.
28th Feb — 28th March	• Final design work and construction
28th March — 28th April	• Review of design work, documentation and showcase; • Future development opportunity outlined; • Further work established with team; • Sharing results, experience and learning; • Short design report.

Expected Budget

The Fair Space project would cover Claire's time at Imperial in line with recommended RCUK PhD stipend 2019/20 annual income, and consumable costs.

Appendix Y: Visual Prompt used during interviews

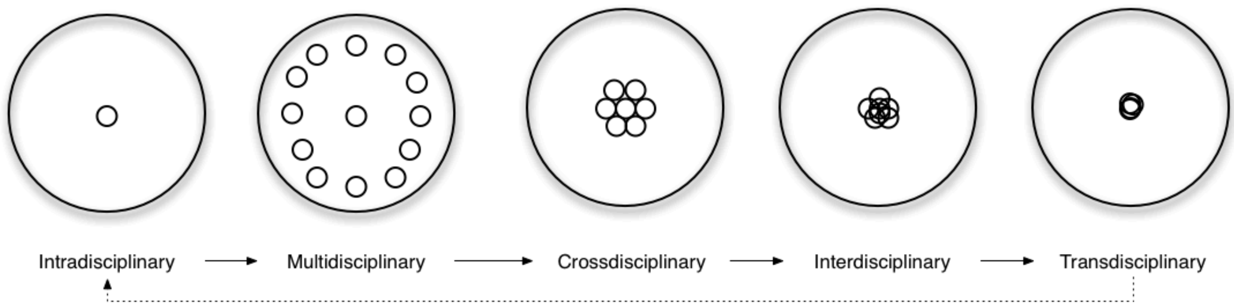

Figure Y.1. *Visual prompt used during CS2 interviews to illicit participants' reflection on the boundaries of their discipline.* [447]

[447] Alexander Refsum Jensenius, ‘Disciplinarities: Intra, Cross, Multi, Inter, Trans’, Post, *ARJ*, 12 March 2012 <https://www.arj.no/2012/03/12/disciplinarities-2/> [accessed 8 August 2025].

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