LEVERAGING FABRIC SUBSTRUCTURE VARIATIONS OF ACTUATOR-INTEGRATED ROBOTIC TEXTILES FOR WEARABLE APPLICATIONS

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THESIS ABSTRACT

TITLE: Leveraging Fabric Substructure Variations of Actuator-Integrated Robotic Textiles for Wearable Applications

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Wearable devices have evolved significantly, progressing from simple touch sensors to advanced hardware like exoskeletons, hearing aids, and space suits. These devices augment how individuals interact with their surroundings and enhance physical capabilities. Despite their effectiveness, many rigid wearable devices, characterized by gears and motors, struggle to adapt to the human body and target specific areas of the body.

The emerging field of robotic textiles focuses on developing thin fabric substrates infused with actuation, variable stiffness, and sensing capabilities. The field distinguishes itself from conventional wearable technologies and soft robotics by harnessing components in fiber forms and leveraging textile manufacturing processes. The bulk characteristics of these textiles are dependent upon the primary fabric structures, whether knitted or woven. Digitally knitted substrates, in particular, offer a highly dense programmable area. Their doubly periodic structure, with each stitch configurable for different elasticities, therefore offers superior programmability and enables diverse 3D structures.

This thesis harnesses the programmability of digital knitting to develop wearable robotic textiles tailored for specific tasks. Setting itself apart from the conventional robotic textile approach, these works emphasize body-conforming geometries and the seamless integration of functional components.

Incorporating materials such as actuators, variable stiffness fibers, and sensors, these substrates are engineered to execute precise mechanical movements and detect tailored deformations necessary for specific wearable tasks. What sets robotic textiles apart is the meticulous

control over each stitch's properties, augmented by the strategic use of functional filaments. This approach situates itself in contrast to traditional wearables, which often rely on rigid components ill-suited for accommodating diverse body shapes and movements.

This thesis further explores the realm of personalized robotic textiles, presenting a case study that highlights their potential as custom wearable devices fabricated through a design tool, bypassing a learning curve required for digital knitting. This case study demonstrates how robotic textiles can provide users with personalized mechanotherapy. By developing a design tool that eliminates the need for extensive knowledge of digital knitting and involving multiple stakeholders, this research aims to empower designers, regardless of their background in knitting or engineering, to create personalized robotic textiles that seamlessly integrate into everyday life.

BIOGRAPHICAL SKETCH

Below is the publication generated during my time as a PhD student. Readers will find that KnitDermis, KnitSkin, KnitDema, and MediKnit are included in this thesis. The remaining publications, while not part of it, have significantly influenced it in terms of materials and design methodologies. These contributions have informed the fabrication of robotic textiles that are performant in various applications.

[1] Heather Jin Hee Kim, Haron Abdel-Raziq, Xinyu Liu, Alexandra Young Siskovic, Shreyas Patil, Kirstin H. Petersen, and Hsin-Liu Kao. "Robotic Barrier Construction through Weaved, Inflatable Tubes." In: *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Detroit, MI, USA: IEEE, Oct. 2023, pp. 8318–8323. ISBN: 978-1-66549-190-7. DOI: 10.1109/IROS55552.2023.10342190. URL: https://ieeexplore.ieee.org/document/10342190/.

[2] Jin Hee (Heather) Kim, Kunpeng Huang, Simone White, Melissa Conroy, and Cindy Hsin-Liu Kao. "KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting." In: *Proceedings of the 2021 ACM Designing Interactive Systems Conference*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, 1183–1200. ISBN: 9781450384766. DOI: 10.1145/3461778.3462007. URL: https://doi.org/10.1145/3461778.3462007.

[3] Jin Hee (Heather) Kim, Shreyas Dilip Patil, Sarina Matson, Melissa Conroy, and Cindy Hsin-Liu Kao. "KnitSkin: Machine-Knitted Scaled Skin for Locomotion." In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3502142. URL: https://doi.org/10.1145/3491102.3502142.

[4] Jin Hee (Heather) Kim, Joan Stilling, Michael O'Dell, and Cindy Hsin-Liu Kao. "KnitDema: Robotic Textile as Personalized Edema Mobilization Device." In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394215. DOI: 10.1145/3544548.3581343. URL: https://doi.org/10.1145/3544548.3581343.

Dedicated to my parents,

to whom I am forever indebted for their unwavering support and belief in me.

Those swirls in the cream mixing into the coffee? That's us.
Ephemeral patterns of complexity, riding a wave of increasing
entropy from simple beginnings to a simple end.
We should enjoy the ride.

— Sean Carroll [34]

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Reflecting on the journey that led me here, I think back to my college days. I'm thankful for Sang Kwon Goo at Ewha Womans University, who taught me the most intricate modeling and surfacing techniques on Autodesk Alias that an industrial designer should be versed in. I learned to interpret the world with vectors and curves and transpose them into 3D space. When I first encountered knitting, I was fascinated by how it parallels the vector-curve world I studied in college. I wouldn't have been able to connect these two worlds without Prof. Goo's teaching.

When I moved to London for my master's degree, Robert Phillips and Bahbak Hashemi-Nezhad at the Royal College of Art showed me how design can cast a societal impact. They led me to investigate how implantable devices reveal the darker side of society, stemming from distrust in central governance and dystopian thoughts of transhumanism. This opened my eyes to how wearable and implantable devices could impact the world. Thank you, Rob and Bahbak.

When I got to Cornell, I realized how much I love pursuing research and almost everything that comes with it. Pursuing a PhD at Cornell has been an incredible journey. I thank my committee members, Cindy Kao, Kirstin Petersen, and Rob Shepherd, for their invaluable insights and guidance along the way.

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To my brother, who is no longer the small kid I used to play with, I'm excited to see where life takes both of us. Your growth continues to inspire me.

Your love and support have kept me going. May every chapter of my life be joyful with you.

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ACRONYMS

ADL Activities of daily living

AROM-PV Active range of motion-pulpa vola

CMC Cayuga Medical Center

COPM Canadian occupational performance measure

DASH Disability of the arm, shoulder and hand score

DEA Dielectric elastomers actuators

DIP Distal interphalangeal

IPC Intermittent pneumatic compression

LCE Liquid crystal actuators

LMPA Low melting point alloys

MCP Metacarpophalangea

MEM Manual edema mobilization

MLD Manual lymph drainage

OT Occupational therapist

PDMS Polydimethylsiloxane

PT Physical therapist

PIP Proximal interphalangeal

RT Robotic textiles

SMA Shape memory alloy

TCA Twisted and coiled actuators

VAS Visual analog scale

WCM Weill Cornell Medicine

9HPT Nine-hole peg test

1

INTRODUCTION

Robotic textiles envision a potentially transformative shift in wearable device design, integrating actuation, computing, property change, and sensing into planar, low-profile fabric structures [26, 28]. This is made possible by fabricating functional components in string forms. In fabricating robotic textiles, these functional fibers can be spatially intermeshed within a planar substrate to create flexible, stretchable structures. Alternatively, components in their string forms can be attached to the fabric surface in a less invasive manner through commonly available sewing or laminating techniques [28]. These methods result in functional devices with a significantly thinner profile and greater compliance than traditional wearable devices.

Despite the potential to transform how we design low-profile wearable devices, robotic textiles still have significant room for improvement. In the past, robotic textiles with pneumatically [26, 47] and electrically driven actuators [28] have been able to emulate the grasp of a hand, bear a load and grasp objects in a controlled laboratory setting [28, 47, 201]. These advances demonstrate the evolution of functional materials in string forms, offering insight into their potential applications as next-generation wearable devices. Nevertheless, the current landscape of robotic textiles has yet to adopt the extensive properties and geometries that can be purposefully engineered into *textile structures* to serve wearable applications.

One of the notable absences in the current landscape is the *body-conforming geometry* of the fabric substrate, which restricts their fit and application areas on the body's surface to flat or minimally contoured regions, limiting their effectiveness in more complex anatomical areas. The human body vastly differs from the structured laboratory settings where traditional robotic textiles have been assessed [28, 201]. The human body's surface is characterized by curves and non-planar geometries, hosting a variety of tactile receptors and exhibiting a wide range of mechanical properties—such as the diverse viscoelasticity of skin and muscle tissues [198]. For robotic textiles to effectively interface with and respond to the human body, they must possess adaptable geometries and flexibility, allowing them to conform to the body's intricate surfaces while performing tasks. However, current designs of fabric substrates primarily focus on fabricating actuators that can create complex motion independently on structured terrains.

Furthermore, the methods used to incorporate functional components in current practices (e.g., sewing or lamination) must be reconsidered to avoid affecting the compliance of the fabric substrate [26]. A typical lamination process would involve heat pressing a film onto a textile substrate, bonding, and then dissolving a water-soluble layer with water [47]. The polymers used to adhere to the actuators compromise the compliance of the fabric as they solidify. Sewing, however, introduces localized stress to the actuators because of areas of tighter or looser stitching, which can lead to uneven force distribution when the actuator is pressurized or activated. More integrated methods that maintain the fabric's flexibility and keep the actuators intact are needed. The more additional materials used to assemble different layers or parts into a robotic textile, the more likely the fabric's compliance will be impacted. Ultimately, multiple fabrication steps limit the scalability of robotic textiles and undermine their accuracy, safety, and reliability when attached to the wearer's body.

This thesis explores fabrication methods for robotic textiles characterized by body-conforming geometries and emergent properties such as elasticity or surface roughness. The textile devices examined in this thesis feature various integrated actuators, perform multiple functions and remain conformal and adaptive to different body surfaces. The research investigates materials, compliant actuators, and textile fabrication techniques to maintain the flexibility and comfort of textiles while fulfilling functionalities for wearable purposes. The goal of developing textiles that can conform to the body's contours and adapt to its movements is to create wearable devices that provide reliable and consistent performance across different wearable applications.

In addressing the current approaches to integrating actuators, this thesis introduces digital machine knitting methods to streamline the process and reduce the use of materials that can compromise the fabric's compliance. By developing specialized fabrication techniques, each project outlined in this thesis incorporates prefabricated *channels* within the device, which then securely enclose actuators without additional heat pressing or lamination. This enclosure extends seamlessly from the base structure (i.e., with no separation between the enclosure and the base fabric). This integration method is crucial for ensuring the accurate functionality of robotic textiles. It enables them to physically actuate and respond in ways tailored to the specific requirements of the tasks performed. Because the channels serve as compliant enclosures, the actuators housed in the substrate guarantee consistent and reliable actuation for various applications.

Finally, this thesis includes case studies to gain deeper insight into increasing access to robotic textiles' fabrication processes. In these case studies, the thesis invites a group of designers with a background in textile manufacturing or related soft robotics and develops a design tool to bypass the programming process required for digital knitting to allow the participation of a broader group of designers. Through a co-design process where engineers and clinicians collaborated from the initial stages of device and tool development, the thesis identifies obstacles in the typical fabrication approaches of robotic textiles. The case studies illuminate fabrication in a broader context involving multiple stakeholders, highlighting the potential of this thesis. The studies also underscore the effectiveness of the design tool in enabling clinicians to actively participate in the development of customized robotic textiles intended for therapeutic use.

1.0.1 *Contribution*

In summary, the major contributions of this thesis include the following:

- Fabrication methods to create two-dimensional (2D) and three-dimensional (3D) forms in robotic textiles by varying the microstructure of the knit in periodic or aperiodic ways. Altering the knit patterns at a microscopic level enables the creation of textiles with tailored mechanical and physical properties, forming structures that conform to the body.

- Fabrication methods that create hollow enclosures to integrate actuators into textiles. These methods minimize the impact on fabric compliance and allow for complex 3D deformation of the fabric.
- A design space for demonstrating a subset of wearable robotic textiles enabled through actuator-integrated and structurally engineered textiles.

1.0.2 *Roadmap*

This section provides a roadmap for the thesis:

- Chapter 2 introduces the related work and provides background on the fundamentals of digital machine knitting and associated software.
- Chapter 3 outlines the design space of this thesis, setting the framework for subsequent chapters.
- Chapter 4 presents Project KnitDermis, an example of an *aperiodically structured* fabric with integrated nitinol actuators in *embedded channels*, demonstrating its tactile applications.
- Chapter 5 presents Project KnitSkin, an example of a *periodically structured* fabric with integrated pneumatic actuators in *embedded channels*, highlighting the benefits of periodic structuring for performing locomotion.
- Chapter 6 introduces Project KnitDema, another example of an *aperiodically structured* fabric with integrated nitinol actuators in *embedded channels*, showcasing its medical application for hand edema.
- Chapter 7 provides a summary and discussion of the design space, synthesizing the insights gained from the projects.

- Chapter 8 concludes the thesis and outlines directions for future work, suggesting potential areas for further research and development.

2

RELATED WORK

2.1 BACKGROUND: VERSATILITY OF KNIT STRUCTURE

Before this thesis explores the integration of digital knitting into wearable robotic textiles, it is essential to understand how knit structures are formed. This section introduces the formation of knit structures and the fabrication steps involved in using an industrial knitting machine. By doing so, this chapter provides the foundation for the concepts and projects introduced in later chapters of the thesis.

2.1.1 *Stitch-by-Stitch Engineering*

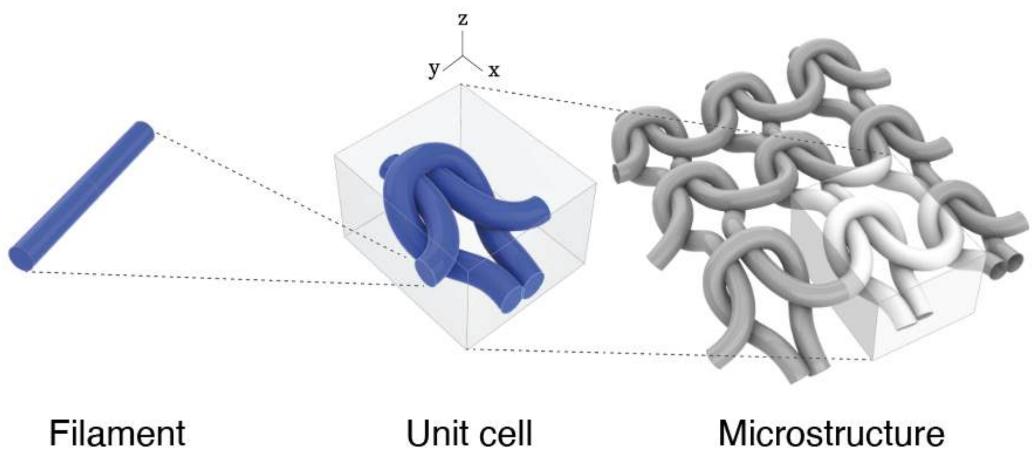

Figure 1: The individual cells that compose the 2D matrix can be digitally programmed to form different stitch types. These cells can further exhibit tunable properties by incorporating active filaments into the stitches themselves.

Knitting—specifically weft knitting explored in this thesis—is a process in which a continuous yarn or filament forms a doubly periodic 2D planar substrate, which can then be interlaced within the plane to create 3D geometries. Regarded as a mechanical metamaterial, knitting leverages different stitches—such as knit loop, tuck, and miss stitches—that exhibit varied levels of elasticity because of their distinct entangled regions between neighboring stitches. The mechanical properties of a knit substrate emerge from the interactions of these individual stitches and substructures.

Each *cell* within the knit structure can primarily form three configurations: knit loop, tuck, and miss stitches. These are created by manipulating the needles into different positions while the yarn horizontally passes across a needle bed. A knit stitch forms a full loop; a miss stitch occurs when yarn passes without engaging with a needle; and a tuck stitch involves yarn being tucked into the latch without forming a full loop. Knitting is a continuous and additive fabrication process in which, after one row (i.e., course) of stitches is knitted, the yarn feeds into the row above. This process results in a doubly periodic formation where a finished piece of knit fabric can potentially be unraveled back into a single continuous yarn (Figure 1).

Furthermore, once stitches are created, they can be transferred to neighboring needles—either along the needle bed or across it, in the case of double-bed machines. These double-bed machines are typically arranged in a V-shape and hence referred to as V-beds. Such manipulations of stitches include *shaping*, where knitting occurs only on selected needles, leaving others inactive, and *stitch transfer*, which refers to transferring stitches either along the needle bed or to the other bed. Transferring stitches can most notably be used to adjust the number of wales in the fabric (i.e., wale refers to a column of loops that run lengthwise). There is also *tubular knitting*, where needles are knitted on alternating beds to create a seamless tube of single-layer jersey structure. Full gauge tubular knitting is limited to single-layer (jersey) tubes. Although various knitting techniques have been adopted by garment makers primarily to adorn or shape the fabric, these techniques have yet to consider their role in the transmission of force when combined with actuators.

At the yarn level, yarns exhibit varying properties depending on their material and structure. For instance, although cotton yarn's elongation at break is usually between 4% and 8%, Spandex yarn's elongation at break can stretch up to 600%. Although altering yarn structure through plying, wrapping, or braiding can make a yarn stronger and more durable, it may not be as effective as the choice of material. In the future, active filaments or materials could potentially offer variable stiffness, energy-efficient shape morphing, and volumetric changes, providing functionalities such as self-fitting, compression, anisotropic shape morphing, stiffening, and damping effects while maintaining the inherent compliance of the knit structure. However, these materials must withstand tension during the knitting process and be flexible enough to undergo the extreme deformation required during knitting.

When these techniques are combined with yarns with adequate properties, they enable the creation of a variety of complex 3D shapes that would otherwise be challenging or even unachievable with weaving or warp knitting. This includes domes and cones, intricate corners, tubes and tubular connections (in seamless knitting), and shapes with integrally knitted holes or cutouts. These various shapes can benefit soft and body-conforming wearable devices by providing fabric substrates with desired properties, that can integrate functional components that are yet to be compatible with knitting.

2.1.2 *Digital Knitting Process*

The most basic way to knit a substrate is to use a manual machine, which does not allow for the programming of designs. In contrast, digital knitting machines enable users to program designs down to the pixel, allowing precise control over the unit cell creation. Digital knitting programming involves a series of procedural steps to translate the design into computer language or code. Digital design interfaces, such as those provided by knitting machine manufacturers STOLL and Shima Seiki, facilitate this process. For example, Shima Seiki's CAD system, known as SDS-ONE, is a fully integrated knit production system that covers all phases, from planning and design to evaluation and production. This system was enhanced in 2007 with the release of SDS-ONE Apex, which focuses on improved 3D knit simulations. The research in this thesis used the Apex version 3 (Apex 3). STOLL's flat knitting machines also provide similar design tools.

On the Apex 3 interface, designers are presented with a blank, pixelated canvas where they can *program* their designs by assigning a pixel with a stitch. Once users complete the design, they generate a series of *option lines* where they further program other details of operation outside the design. An option line is essentially a programming feature used to control and switch between different yarn feeds, color selections, or stitch types during the knitting process. This programming allows a user to not only modify the knit stitches conducted by needle operation but also to control the machine's operations such as stitch size, takedown (the mechanism that applies consistent downward tension on the fabric being knitted), and feeder control. These settings can be adjusted to influence the properties of the knitted substrate. The data generated by designers is saved in an `.SKNP` file, accompanied by `.000` and `.QFD` files. The `.000` file is then fed to the knitting machine to produce the fabric.

2.1.3 *Computational Knitting Process*

Despite the immense potential of digital knitting as an additive manufacturing technique, the process of pixel-based programming can be daunting and involve a steep learning curve. In response, HCI researchers have made significant advancements in making this technology more accessible. For instance, McCann et al. [146] developed a compiler specifically designed to translate high-level shape primitives, such as tubes and sheets, into low-level machine instructions. Similarly, Narayanan et al. [161] introduced a computational method for converting mesh-based geometric inputs into instructions suitable for computer-controlled knitting machines. Further research has also explored the integration of visual programming interfaces, enabling the creation of 3D objects and doubly-curved surfaces with greater ease [115, 162]. These developments are crucial in reducing barriers to entry for users new to digital knitting technology.

2.2 TEXTILE-BASED WEARABLE DEVICES

Textiles offer significant potential as wearable devices because of their ubiquity throughout human history and their inherently flexible nature. It is not an overstatement to say that the transformation of textiles into wearable technology initially began with the development of e-textiles. Broadly defined, e-textiles are fabrics that have electronic components and circuits woven into their structure, enabling them to sense, compute, and communicate. This integration exemplifies how conductive yarns or filaments can replace traditional traces in PCBs or wires in electronic devices.

The progress in e-textiles has largely been facilitated by the fact that conductive yarns share similar mechanical properties with conventional yarns. This similarity allows them to be seamlessly incorporated into textiles using standard textile fabrication methods such as sewing, weaving, braiding, or knitting. As a result, a wide variety of textile structures has been successfully implemented as sensing interfaces.

Knitting has been favored for sensing due to its superior elasticity. Continuous interlocking loops result in interfaces that have considerable stretch, enhancing knit fabric's ability to serve as strain sensors and electrodes [14, 148, 172, 176, 185, 252]. For instance, Ou et al. [172] presented a machine-knit resistance-changing elastic stretch sensor. Despite insufficient accuracy in reading, Wijesiriwardana et al. [252] developed knitted resistive transducers as well as wearable electrodes and solenoids. Paradiso et al. [176] integrated machine-knitted piezoresistive sensors into a garment, insulating the components using a tubular intarsia technique.

The approach to incorporating actuation within textiles began with the integration of textile elements into mechanical components, specifically pneumatic actuators. An example of this is the use of a braided sheath in McKibben actuators, which were first developed in the 1950s [242]. In these actuators, the braided sheath enclosed a pneumatic tube; as the tube expanded with increased air pressure, the braid expanded radially but contracted longitudinally. This design enabled McKibben actuators to exhibit variable compliance, which changed based on the pressure within the tube, allowing for precise control over movement and force exertion. Woven textiles, known for their high tensile strength and limited elasticity, have also been particularly effective in this context. They are often used alongside pneumatic actuators as a strain-limiting layer, enhancing the durability and functionality of the actuators. The advent of soft robotics has further boosted the use of woven layers—often in combination with robust materials such as Kevlar yarn—to serve as flexible yet restrictive components that control and limit the expansion of the actuators. Knitted structures have also found significant applications in tandem with inflatable actuators because they can be programmed with varying degrees of elasticity. These knitted coverings facilitate a range of motions of pneumatic actuators, including bending and twisting. These properties are particularly useful for creating dynamic and reversible movements.

Subsequently, there were efforts to incorporate materials with fiber forms capable of generating force. Materials such as shape memory alloys (SMAs) have been known since the 1930s [41], and research on integrating them into fabrics began to accelerate in the 1990s. Since then, SMAs have been extensively used, not only sewn onto plain fabrics but also integrated into woven and knitted structures for a variety of applications. In HCI, these shape-changing textiles have been developed for purposes such as expression [21, 36, 88, 124, 241], protective heat insulation [284], medical and therapeutic uses [60, 79], donning assistance [135, 149], compression garments [79], input sensing [234], robotic applications [38, 273, 274], and interactive architecture [45, 50]. In addition to SMAs, other materials to induce the deformation of fabric included passive, responsive materials [103, 203, 204], tendons or structural mechanisms [8, 133, 181], and phase-changing actuation [202].

2.3 ROBOTIC TEXTILES COMPOSITION

Robotic textiles attempt to find an intersection between textile technology and soft robotics. Robotic textiles move beyond using fabrics merely as coverings for actuators, to fully integrating actuators, variable stiffness fibers, and sensors within the fabric structure itself. The goal is to maintain the inherent architectural integrity of traditional textiles while imbuing them with advanced functionalities. This integration allows the textiles to respond dynamically to deform and complete tasks.

2.3.1 *Fabric Substrate*

The role of the fabric substrate is critical in robotic textiles, but traditionally its use has been somewhat limited. Conventional robotic textiles primarily employ the fabric substrate to attach components, where a flat fabric serves as the base onto which various actuation elements—such as sensors, actuators, and VSF—are sewn or laminated.

A growing body of work in HCI and other engineering fields introduces advanced approaches. By deliberately designing the fabric substrate with specific desired properties, such as frictional or elastic anisotropy, the functionality of these textiles can be significantly enhanced. When these specially designed substrates are coupled with appropriate actuation mechanisms, they can perform complex tasks. For example, fabrics engineered with instability can grasp objects with a single tendon [10], and fabric substrates with varying frictional properties can be used to perform locomotion [119].

Furthermore, fabric substrates can be fabricated in a single step during knitting to achieve self-standing 3D shapes. In the past, creating 3D shapes that conformed to the body required stiff panels of fabric to be patched together. However, digital knitting technology allows the creation of intricate 3D shapes directly from the knitting process itself, elevating knitting from other fabric manufacturing methods.

Moreover, substrates can also be structured to provide enclosures for functional components, keeping them securely in place for precise actuation and ensuring consistent contact between the body and the textiles. By infusing fabric substrates with desired structures, it becomes possible to develop more responsive, adaptive, and functional robotic textiles. These textiles find applications in diverse fields ranging from wearable technology and fashion to medical devices, offering enhanced comfort, performance, and versatility to users.

2.3.2 *Functional Component in String Form*

Actuators play a pivotal role in robotic textiles by generating forces that ultimately deform the fabric substrate. A promising approach involves embedding shape-change capabilities in passive textiles using actuators shaped like long, thin strings. Unlike planar or volumetric actuators, these string-like actuators possess low bending moduli, enabling them to adapt to the body's contours and deform within the textile. These actuators can be made from a single responsive material—such as dielectric elastomers DEA, SMA, or LCE—or from a combination of materials with varying stress responses.

Contraction is a particular type of shape change that has been extensively used. For example, SMA wires and springs have been used in numerous applications because of their ability to handle large strains, including in haptic devices [11, 118, 224], compression technologies [70, 83, 265], adaptive garments [43, 63, 135], and expressive on-body devices [126]. Twisted and coiled polymer actuators (TCA or TCPA) offer reversible contraction under thermal loads. When configured as coils, drawn polymers such as nylon monofilaments contract because of anisotropic thermal expansion. TCAs can be as thin as 235μm in outer diameter and have been integrated into fabrics or encapsulated in elastomers to function as standalone actuators. Although thin hydrogel fibers have demonstrated thermally driven contraction, their use in HCI remains limited [87].

In addition to contraction, a combination of materials with different responses to pressure and strain, such as silicone rubber paired with a strain-limiting component in string forms, can be used to generate bending. These materials provide flexibility and adaptability essential for rehabilitation applications, matching the kinematics of the body with their infinite degrees of freedom. Options for strain-limiting components include bellow sheaths [119], fibers [48, 256], braids [116], or textile sheaths [116, 139], making these reinforced pneumatic actuators a versatile and effective choice for textile-based actuation systems.

In addition to actuators, components with variable stiffness can enable textiles to bear an external load and ultimately facilitate sophisticated actuation or the development of subsets of novel applications that are centered on protective and impact-resistant textiles. In addition to robotic textiles, several approaches have been explored to introduce variable stiffness into mechanical systems [159, 199, 219], including phase transition methods [231] and jamming techniques [173] within HCI. However, the realization of these systems in string forms to achieve compatibility with textile surfaces has been hindered by hardware constraints (i.e., the restricted extent to which jamming or spring-based systems can be miniaturized), prompting researchers to explore material property changes. VSFs typically combine materials less responsive to thermal load (e.g., silicone rubber) and those thermally responsive at wearable temperatures (e.g., liquid metal or low-melting point thermoplastics). Materials such as liquid metal or thermoplastics are primarily responsible for adapting stiffness, while silicone rub-bers encapsulate the primary materials in place and preserve their form while undergoing a phase or glass transition. This is exemplified by research in which thermoplastic-coated VSF demonstrated load-bearing capabilities [273], performed sophisticated deformation [28], and performed move-and-hold to facilitate finger motion [38]—all enabled by material property changes. Other disciplines have used phase-changing materials such as low-melting-point alloys (LMPAs) to develop fibers [232].

2.4 FABRICATION PROCESS OF ROBOTIC TEXTILES

There are two primary methods for integrating fabric substrates and actuators to create robotic textiles. The first method involves seamlessly incorporating actuators or components directly into the fabric structures, either knitted or woven, when these components have properties similar to yarn [80]. However, because of the limitations of available actuators that have flexibility combined with high energy density to generate force, this method of integration is restricted to a few specific end uses. Most robotic textiles cannot integrate actuators using a monolithic fabrication process and must incorporate them during post-substrate manufacturing instead.

The attachment of functional components to robotic textiles typically involves methods such as sewing or lamination. Sewing allows components to be fixed directly onto the fabric substrate, but this can introduce localized stress and may not always provide a complete insulation or protection barrier between components and the skin. Alternatively, lamination involves encasing the components between two fabric layers using adhesives or heat if the two fabric layers are thermoplastic, both of which can significantly affect the textile's overall flexibility and compliance—attributes crucial for wearability.

A potentially more effective approach could be the use of an enclosing structure that is continuous with the fabric substrate. This would allow seamless integration of components and ensure insulation measures without compromising the functionality or comfort of the textile device. Such an approach not only enhances safety but also ensures that the functional components are precisely positioned for accurate interfacing with the user's body while allowing component replacement.

3

DESIGN SPACE

Robotic textiles differentiate themselves from soft robots made of silicone, which also generate comparable non-linear and continuous deformations. Robotic textiles [28] emphasize meta-material fabric structures and maintain the form of actuators close to that of fibers. Research has shown various methods to integrate such components into fabrics. However, the fabric substrate often remains a passive, non-functional planar material, serving only as a host for attaching functional components.

Figure 2: The LZR Racer swimsuit prevents the creation of vortex and reduces fluid resistance by having micro-textures on its surface. The swimsuit was banned from being worn.

Throughout human history, significant effort has been devoted to tailoring fabric to fit the wearer's body and enhance human performance [247]. From everyday clothes, functional gloves, and protective equipment to specialized functional swimwear, manufacturing processes have been developed to transform the fabric into body-conforming pieces to fit the human body. These fabrics extend beyond snug-fitting devices, enhancing the wearer's abil-

Figure 3: The BioSuit, embedded with shape memory alloy, is designed as an alternative to the existing stiff and gas-filled space suits.

ity to complete tasks more efficiently. One example of this is the LZR Racer [213], a skin-tight swimwear with micro-textures that minimizes drag between the body and the water while allowing free movement. Similarly, compression garments are designed to fit the body snugly, distributing pressure evenly across areas requiring compression. These garments demonstrate how well-shaped devices conform to our body contours and contribute to functionality and comfort. Expanding the functionality further, garments with integrated actuators could emerge. Bio-Suit, a body-conforming and whole-body textile device integrated with SMAs [206], is a counter-pressure garment that replaces traditional bulky, gas-filled spacesuits by incorporating SMA actuators along nonstretch skin lines. This design provides the necessary pressure while maintaining flexibility in a skin-tight form, which is crucial for reducing the stiffness of existing gas-filled spacesuits in space environments. Extending this concept, actuation across the entire garment can be achieved using yarns with shape-change capabilities. Yarns processed with polymers have been interwoven with other yarns to create knit structures, which allow a custom fit through selective heating [229].

This thesis aims to make the current approaches to fabricating robotic textiles more suitable for wearable applications by creating complex textile geometries that conform to the body and apply to specific tasks performed on the body. With modified geometries, these textiles can alter the physical and mechanical properties of fabrics locally or globally. These modified textiles could also create specific motions when integrated with actuators. Leveraging string-form actuators and drawing from traditional knit techniques used in garments, the devices showcased in this thesis are designed to contribute to wearable devices that conform to the body and generate motion while worn.

3.1 CONSTRUCTING THE DESIGN SPACE FOR KNITTED ROBOTIC WEARABLES

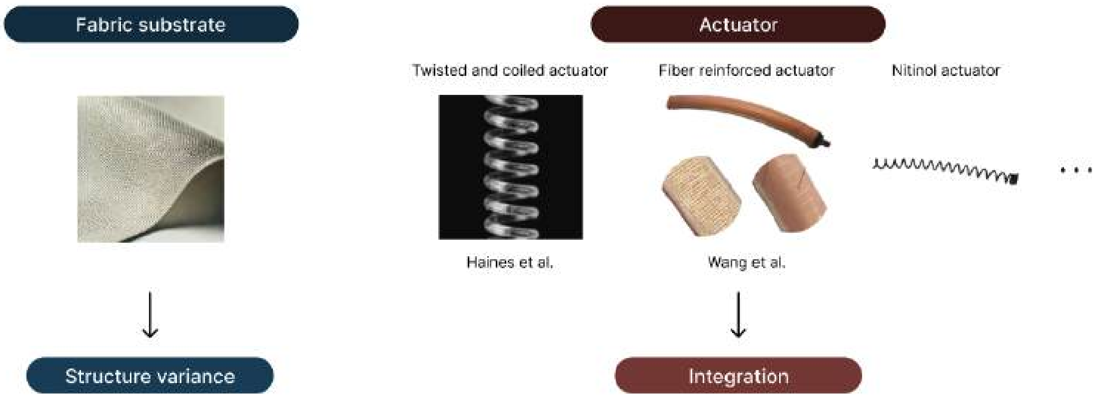

Figure 4: The design space consists of two primary parameters: the *fabric substrate* and the *actuator*. Different classes of soft actuators, such as twisted-and-coiled or fiber-reinforced actuators [85, 245], have been integrated into fabrics in the past.

Transitioning current fabrication approaches in robotic textiles to wearable applications poses unique challenges. Achieving practical wearability requires consideration of wearability factors [72] and employing diverse fabric manufacturing techniques to ensure that the deformation created is suitable for human users. For these textiles to have actuating capabilities and perform specific tasks on the human body, two main factors are crucial: the design of the *fabric substrate* and methods for *integrating actuators*.

Fabric substrate is one of the two primary parameters that construct the design space of this thesis. This thesis chooses digital machine knitting as the primary fabrication method because of the extensive programmable elasticity of knit substrates. This programmability arises from manipulating the periodic structure of knit fabrics, ranging from individual stitches (knit, miss, and tuck) to the U and V directions of the knit loop matrix. Modifying the structure allows the substrate to be infused with emergent properties, creating conformal shapes, physical textures, and variable elasticity [211].

This parameter considers how the microstructure of the knit is configured across the global structure—hence the sub-parameter *structure variance*. Structural variance pertains not only to geometry but also to the mechanical properties of the fabric substrate. For example, by periodically arranging the microstructure, one could engineer a knit substrate to exhibit a specific surface roughness. In contrast, if a substrate's microstructures are arranged aperiodically, the substrate can achieve 2D or 3D shapes, determining the overall conformity of the device to the body surface. Therefore, arranging the knit's microstructure has a significant impact on the emergent properties and nonplanar geometries of the fabric base.

The *actuator* is the other primary parameter that explores how fabric substrates integrate actuators to generate motion and deform the fabric substrate. Actuators can be embedded in a device to mechanically stimulate the body or perform tasks while on the body surface. The integration methods for actuators are crucial in driving and regulating mechanical movement, leading to subparameter *integration*.

In addition to the actuators themselves, the way in which they are *integrated* within the fabric substrate is critical—especially for wearable applications. The integration method significantly affects the precision of actuator positioning. Manual processes often result in fabrication inconsistencies, and methods that permanently embed actuators may not be favored when considering the replacement of actuators in real-world applications. Furthermore, the inclusion of additional materials in the integration process, such as adhesives and extra layers, is likely to negatively impact the inherently desirable properties of fabrics, such as flexibility and breathability. Therefore, the method of integrating actuators is a parameter that requires careful consideration when designing wearable robotic textiles.

The following section introduces a design space defined by parameters critical to wearability. This space could guide future design directions for robotic textiles in various wearable applications.

3.2 FABRIC SUBSTRATE

By examining robotic textiles as wearable devices that interact with the body, this thesis first explores the parameters of the *fabric substrate*. Not unlike the role of silicone in on-skin devices—where silicone encapsulates electronic components and mediates contact with the body—textile substrates offer comparable elasticity and compliance. However, unlike PDMS or silicone rubber, fabric substrates are engineered as metamaterials, which differentiates them. By manipulating individual knit loops within a lattice structure, one can tailor the geometries and properties of knitted substrates to meet specific application needs. The *structure variance* parameter explores how microstructures are arranged within the 2D matrix of the knit stitch program, which can be programmed to transition from homogeneous stitches to varying in a periodic or aperiodic manner and ultimately to form complex 3D structures. This parameter is crucial because it allows for the customization of the fabric's mechanical and physical properties and geometry. By manipulating the substructure, we can design fabrics that conform to various body shapes and exhibit specific characteristics—such as anisotropic elasticity, stiffness, or surface roughness—depending on the intended application. This ability to fine-tune the fabric at a microstructural level opens up new possibilities for creating advanced, multifunctional robotic textiles.

3.2.1 *Structure Variance*

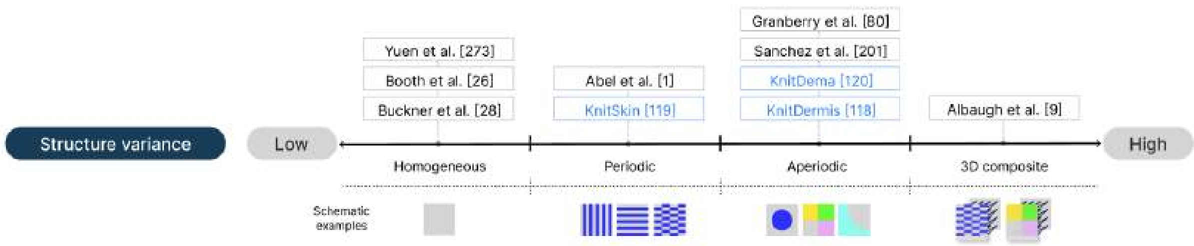

Figure 5: The degree of variance across microstructures can range from low to high. Blue labels indicate works from this thesis, while black labels indicate related work.

Some fabric manufacturing processes enable programmable geometry to a certain extent. Weaving, for example, offers limited freedom in geometry manipulation because the warp remains stationary while the weft (crosswise) can be programmed to create various patterns. In contrast, digital knitting allows for a more extensive programming of geometry, which is key to eliciting emergent properties unique to this method.

We can analyze the fabric substrate by examining how its substructures vary—hence the term *structure variance*. At the most basic level, there may be a substrate composed of *homogeneous* stitches; as the name suggests, a homogeneous structure contains identical stitches throughout. Despite the low variance in stitch pattern, the constructed structure exhibits elasticity that emerges from the fabric's architecture rather than relying solely on the yarn's properties. This inherent elasticity is a result of the way the stitches are interlinked, providing stretch and flexibility to the fabric even when using yarns with minimal elastic properties. Booth et al.'s fabric, despite being homogeneous, exhibits elasticity to withstand deformation as the actuators bend [26]. Buckner's work has attached actuators to a fabric substrate that is knitted with a uniform structure and porosity [28]; similarly, variable stiffness fibers have been attached to a fabric substrate without varying the substructure through sewing [273].

Moving beyond the homogeneous structure is a fabric substrate that contains stitches in a *periodic* arrangement. This periodicity in the knit structure can infuse the structure with amplified properties. Given that knitting inherently forms a doubly periodic structure, variations can occur in either the U or V directions or both. When stitches display periodicity, they can exhibit emergent properties such as elasticity or specific textures. Garter and rib structures are notable examples where stitches vary periodically, demonstrating significant elasticity and suitability for parts designed to endure large strains. More specifically, a rib structure in knitting arranges *knit* and *purl* (i.e., when the yarn is placed facing front) stitches in alternating columns, providing greater elasticity across the width of the substrate. Abel et al. have knitted single periodic structures (e.g., garters and ribs) with SMA, where the resulting fabric texture influenced the global deformation of the actuators [1]. KnitSkin, in this thesis, uses periodically patterned monofilament to infuse the engineered surface roughness that emerged from its texture and enable locomotion [119].

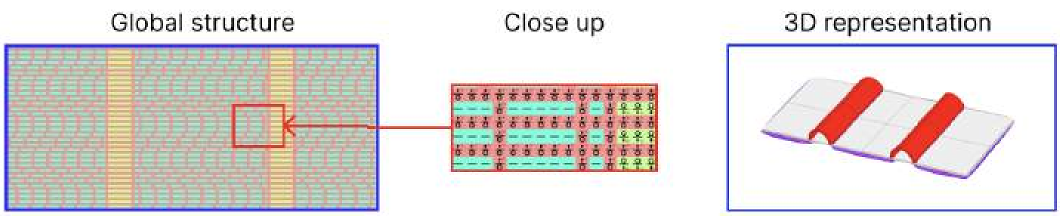

Figure 6: A schematic of a structure with periodicity and its 3D representation as a knitted object. The close-up displays cells with different types of stitches. Note that the 3D outcome depends on the elasticity of the materials used. Red indicates propped-up half-cylinder channels, gray represents the planar substrate, and purple shows the textured surface resulting from the pattern.

Alternatively, a knit structure can be engineered in *aperiodic* configurations to shape a planar substrate through course-wise stitch transfer and to create 3D shapes by suspending stitches. With this method, there are no repeated substructures in either the course (V direction) or the wale (U direction) of the fabric. One example of this technique is *short-rowing*, where partial courses (i.e., rows) of knitting are created by turning the structure before reaching the end of a full course, knitting only a portion of the stitches. This approach allows for greater versatility and complexity in the design, enabling the creation of unique shapes and forms that are not possible with periodic structures. In this manner, Granberry et al. constructed a substrate with multiple distinct substructures intermeshed with SMA, where each substructure deforms in a specific way. The resulting SMA substrate served as a self-fitting interface [80]. Sanchez and her colleagues have constructed a sheath that combines three different substructures to create a sequence of motion that propels through a confined space when integrated with a pneumatic actuator [201]. Similarly, KnitDermis—as introduced in this thesis—arranges its structure in an aperiodic composition to achieve 3-dimensional shapes [118]. In contrast, Knit-Dema creates various in-plane geometries by knitting substrates without periodicity [120].

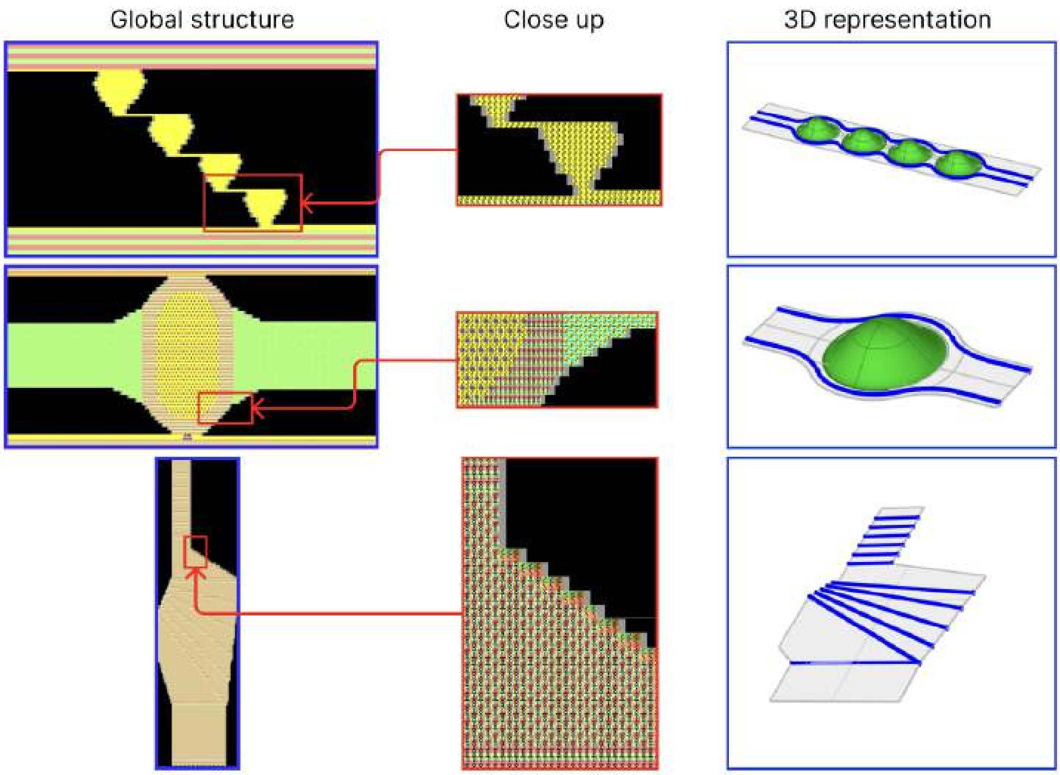

Figure 7: The first column displays schematics of structures from this thesis without periodicity. The close-up in the next column shows stitch notation. The right column illustrates the 3D representation as a knitted object, which depends on the elasticity of the materials used. Green indicates projective domes, gray represents the planar substrate, and blue shows integrated channels.

At a more complex level, a *3D composite* structure involves transferring yarn across two fabric substrates, adding dimensionality and degrees of freedom. This technique can create an almost solid-like bulk composite structure that can be engineered to drive specific motions or serve shock-absorbent applications. For example, Albaugh et al. used nylon filament transfers between two layers of knit substrates to create a solid-like composite that serves as a gripper with an integrated tendon [9].

Such attuned structures listed above not only enhance the physical and mechanical properties of the substrate [119] but also enable the creation of convex and projective geometries [118] and facilitate the precise embedding of functional components in desired positions through the creation of channels [120]. This dual capability underscores the importance of structural tunability in the design and functionality of advanced robotic textiles. The following chapters provide examples of projects that program the fabric substructures to vary in a periodic and aperiodic arrangement.

3.3 ACTUATOR

A limitation that impedes the safe functionality of current robotic textiles when attached to human users is how functional components—such as actuators, variable stiffness fibers, or sensors—are integrated within the fabric. This *integration* plays a crucial role in determining the deformation of the fabric, and depending on how the components are integrated, it significantly affects the fabric's compliance. Proper integration is essential because it dictates how the fabric will flex, stretch, and conform to various shapes, impacting both its functionality and comfort.

This *integration* process involves determining whether a component can be incorporated structurally within the substrate or more at its surface level. Although actuators, such as SMA wires, can be knitted or structurally integrated, most other components require different integration methods. An example of integrating these "incompatible" components is the Bio-Suit [206], a counter-pressure garment designed to replace traditional bulky, gas-filled spacesuits. It incorporates SMAs along nonstretch skin lines, providing necessary pressure while maintaining flexibility—key for addressing wearability in space environments.

3.3.1 *Integration*

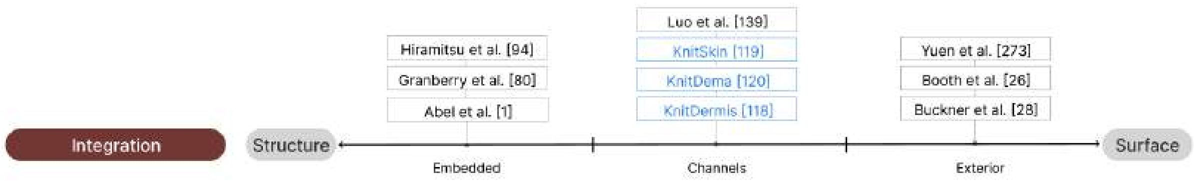

Figure 8: The scale ranges from structural to surface-level methods that compose the parameters for integrating actuators.

The methods for integrating components into fabric substrates are largely dictated by the properties and dimensions of the components as well as the capabilities of a knitting machine. When an actuator or component has sufficient flexibility and elasticity to endure the stress during the knitting process, it can be seamlessly incorporated as part of the knitted structures—effectively integrating it within the textile itself. This type of *embedding* at the structural level is well-demonstrated in the work of Abel and Granberry et al. and is considered permanent because replacing a component once embedded is challenging without dismantling the device [1, 80]. In a woven structure, by contrast, actuators can be woven in as a weft (which passes under and over the warp) while keeping the other yarn non-functional and non-responsive [94]. This is considered another way to embed actuators.

Figure 9: Fabric channels securely incorporate actuators and demonstrate safe medical applications.

Alternatively, the creation of fabric conduits involves structurally modifying the substrate to create a hollow "channel" within a double-layered knit structure. This channel serves as a conduit, with the fabric layers acting as a protective sheath, facilitating the easy swapping of components while securing their position. This *channel* approach is particularly advantageous for wearable applications that require precise force exertion and accommodate a variety of actuators. For example, although Luo et al. incorporate soft pneumatic actuators of considerable size to generate forces of 5 ∼8N [139], the same fabric channel structure can be used to incorporate nitinol actuators with a millimeter diameter [118, 120], or smaller actuators such as those used in KnitSkin [119]. The channel approach—the main technique demonstrated by this thesis—significantly enhances wearable devices' functionality, durability, and versatility. Structurally modifying the substrate to create a channel within a double-layered knit structure holds components in place by the fabric layers that act as an enclosing sheath. This not only shields the components from external stresses and wear, extending the device's lifespan, but also allows easy access for swapping out or upgrading parts without damaging the surrounding fabric. Additionally, this method ensures that components are securely positioned while having a minimal impact on the fabric's compliance.

(a) Nike's FlyKnit sneakers have threads heat-pressed onto a fine-gauge knit surface.

(b) Pneumatic actuators in OmniSkin [26] are glued onto fabric.

Figure 10: Lamination examples.

Moving a scale away from the structural level, *exterior* refers to placing a component onto the surface of a fabric piece. One method includes lamination, as demonstrated in the work of Booth et al., which involves placing an actuator between two substrates—either both textiles or one textile and a polymer sheet [26]. In the case of laminating two fabric layers, a component is sandwiched inside and the fabrics are bonded together using adhesive (Figure 10b). Alternatively, a component can be placed on top of a fabric substrate and heat-pressed with a thermoresponsive polymer (Figure 10a). A prominent example of this technique is Nike's FlyKnit, where wires are laminated atop knit panels with a transparent polymer. This method secures the wires for structural purposes. Heat-sealed or crosslinking-induced lamination permanently encases the component, and although bonded fabrics can be detached, they may damage the components. The use of adhesives and additional layers in lamination reduces the fabric's flexibility and obstructs its breathable properties. Therefore, lamination represents one of the most enduring forms of component integration, impacting the final product's flexibility and breathability.

Another method for *exterior* integration is sewing, where components are affixed by stitches directly onto the substrate. This method permits the detachment and reattachment of actuators, offering greater versatility in component placement and replacement compared to more permanent methods such as embedding or lamination. Buckner et al. have sewn SMA ribbons onto fabric, which allowed the flattened ribbon to bend and buckle in-plane [28]. Following a similar method, Yuen et al. have sewn variable stiffness fibers onto a fabric substrate [273].

Exploring methods for applying active materials directly onto the fabric could potentially be beneficial to further enhance the integration of actuation capabilities within a fabric substrate. This approach would involve surface-treating one side of the fabric with materials capable of generating motion. By depositing these active materials, the treated side of the fabric could actively respond to stimuli—such as electrical currents, temperature changes, or other environmental factors—resulting in controlled movements or adjustments in the fabric's structure.

3.4 Summary of the Design Space

By incorporating parameters related to the two main components of constructing robotic textiles—the fabric substrate and actuator integration—the design space is expanded, allowing us to connect various scales to explore previously untapped areas of the design space. By plotting the two subparameters on an x-y graph (Figure 11), one can investigate different aspects of task-specific wearability by interconnecting distinct scales. This methodology facilitates a structured approach to tailoring the design and functionality of robotic textiles according to specific requirements.

Much of the previous work has focused on developing actuators in fiber forms; many variable stiffness fibers and adapted nitinol actuators are helpful examples. These actuators have

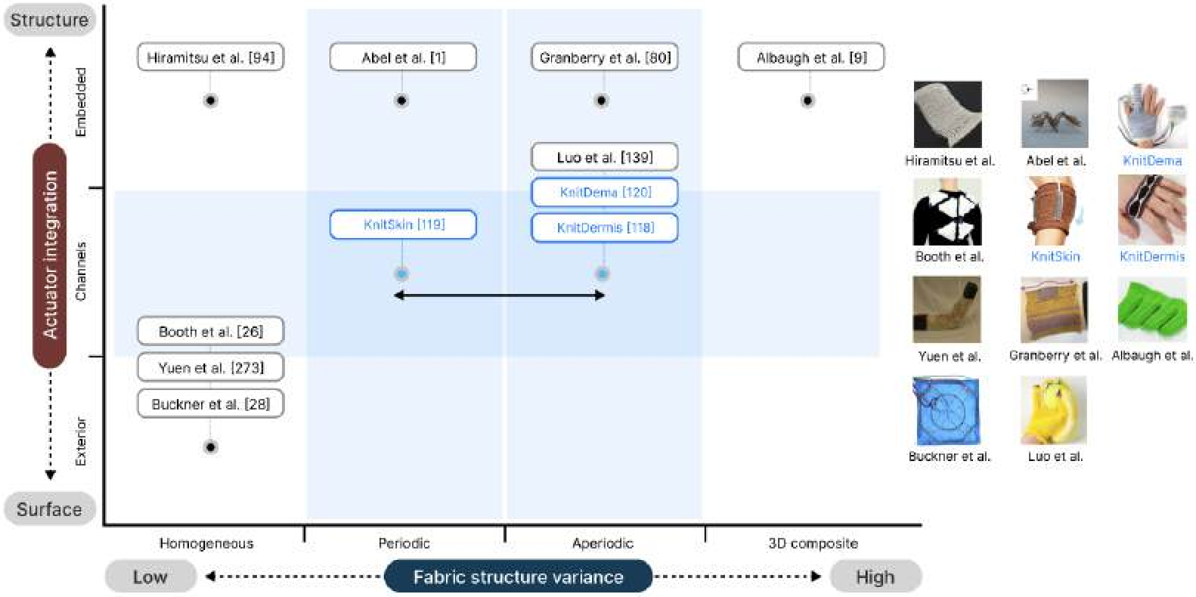

Figure 11: Situating the literature and the dissertation projects in the design space.

been attached to substrates that are not specifically engineered or have engineered geometry. For this reason, much previous work is bundled in the exterior-homogeneous cell.

With actuators that can withstand stress during the fabric manufacturing process, some approaches have embedded actuators as part of the fabric's structure. This embedded integration covers a range of structural variances, including homogeneous, periodic, aperiodic, and 3D composite structures.

This work fills a gap in the integration space by creating enclosing spaces within the fabric—i.e., fabric channels—to accommodate various types of actuators without affecting the fabric's compliance. This approach allows for the seamless embedding of actuators, maintaining the fabric's flexibility and adaptability.

Throughout my research, I have explored knit structures with both periodicity and aperiodicity. I have demonstrated how these two structural variations result in specific properties and body-conforming shapes. Periodic structures allow for emergent properties that are useful in tandem with actuators, while aperiodic structures enable more complex and tailored geometries that conform to the body.

The following chapters of this thesis present the design, implementation, and evaluation of robotic textiles developed for specific tasks. Each project discussion will include an analysis of where it fits within the design space, providing a structured reflection on its positioning and how it aligns with the intended functionality. Through this examination, this thesis aims to demonstrate the practical applications of these textiles in real-world scenarios, offering insights into their potential impact and future developments in the field.

4

ROBOTIC TEXTILES FOR TACTILE FEEDBACK

4.1 KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting

This chapter explores digital knitting as a medium for creating various geometries designed to conform to the body's non-planar shapes. Traditionally, developing tactile devices for these complex-shaped locations has been challenging and often avoided, explaining why many devices disproportionately target the forearm.

This chapter discusses KnitDermis, which is based on a previously published paper. We have developed eight tactile interfaces using various knit structures. These interfaces incorporate shape memory alloy springs into fabric channels, specifically designed to deliver stimulation at targeted locations. The embedded actuators provide four types of tactile feedback, either by directly deforming the skin or by continuously stimulating Merkel cells.

In this context, the work is situated within the *aperiodic* structure scale of the *fabric substrate* parameter in the design space, exploring the conformal geometry of fabric substrates. The devices introduced in this chapter utilize *channels* created within fabric substrates to integrate nitinol actuators.

I worked with an excellent team consisting of Kunpeng Huang, Simone White, and Melissa Conroy, all from Cornell University, under my advisor, Cindy Hsin-Liu Kao. Kunpeng Huang developed the hardware board, while Melissa Conroy tutored and closely guided me on realizing the machine knitted structures. I will use "we" throughout this chapter to denote our collaborative work in developing the device. KnitDermis is based on the paper I primarily authored, entitled "KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting," published in ACM DIS 2021 [118].

4.2 INTRODUCTION

Haptic devices can deliver rich information to the user's skin in a discreet and eyes-free fashion. Thanks to mechanoreceptor cells, our skin is sensitive to a wide-range of tactile cues. The receptivity of mechanoreceptors has led current research to focus on enhancing tactile resolution [58, 89, 266]. However, the current methods for high-resolution outputs are often bulky and not body conformable. They often require additional rigid devices (i.e., pumps or compressors [77, 89, 92]), which may not be wearable and can constrain the use of the devices to certain body locations [77, 127]. Furthermore, each tactile output often requires distinct actuation mechanisms, making it challenging to combine different techniques for designing richer haptic sensations. The lack of skin conformity and versatile actuation mechanism in current tactile devices limits their expressiveness.

We introduce KnitDermis, a knitted on-body interface that can distribute expressive tactile stimuli to a variety of body locations. Our method integrates *shape memory alloy (SMA) micro-springs* utilizing SMA's yarn-like property to traverse freely within machine-knitted channels for actuation. SMA micro-springs have an internal diameter of less than a millimeter, making them analogous to yarn, and allowing them to be integrated into knitted substrates. Large strain and axial displacement are additional merits that micro-springs introduce to KnitDermis. In order to deliver varying tactile outputs from identical structures, we design channels that manipulate the travel of micro-springs. We knit versatile channels that can position the springs into closed, free-form, and intersecting curves.

These integrated channels work in tandem with knitting's unique shaping capabilities to "sculpt" the tactile interfaces onto diverse body topographies. By actuating the skin where the KnitDermis interface is attached, or via actuating the interface itself for deformation close to the skin, KnitDermis can deliver pinch, twist, compression, and brushing gestures.

KnitDermis uniquely departs from the form factor of traditional tactile devices, presenting slim and conformable form factors that behave like a second skin. The resulting thin and soft substrates enable the distribution of silent tactile outputs to under-explored body locations.

In this paper, we introduce the actuation mechanisms, design factors, and fabrication approach of four distinct knitted tactile output sensations: compression, pinching, twisting, and sliding. We also present a series of case studies as our primary tool to carry out research through design methodology [282], which distribute tactile outputs to a range of body locations under-explored by other works. We conducted a preliminary user study experiment to understand the effectiveness and comfort of KnitDermis interfaces, along with semi-structured interviews gauging user perceptions and envisioned applications for the interfaces.

By bridging the realms of textile knitting and haptic interfaces on the body surface, we introduce an alternative approach for crafting *soft* haptic feedback interfaces in Human-Computer Interaction (HCI). Our contributions include:

- We introduce machine knitting as a fabrication method for generating soft tactile interfaces embedded with SMA micro-springs. Our fabrication approach takes advantage of (1) the shaping capabilities offered by knit structures to create substrates which conform to challenging body locations under-explored by other works, including protruded body joints and convex (hollow) body locations; (2) the versatility of knitting to create structurally-integrated free-form channels which allow for unconventional patterning of SMA micro-springs for diverse outputs. We detail the design factors contributing to a rich palette of knit tactile interfaces.

- We present eight case studies from the lens of research through design: each interface leverages a unique combination of knit structures (shaping and channel design) to deliver tactile feedback from compression, pinch, twist, to brushing on different parts of the body.

- We conduct a study which provides insights into the effectiveness and comfort of KnitDermis-based tactile feedback across different body parts, and unpack the personal meanings and social functions KnitDermis interfaces foster within one's everyday dress.

4.3 RELATED WORK

4.3.1 *Dynamic and Knitted Soft Interfaces*

Dynamic shape-changing textiles have been explored for expression [21, 36, 88, 124, 241], protective heat insulation [284], medical and therapeutic purposes [60, 79], donning assistance [135, 149], compression garments [79], input sensing [234], robotic applications [38, 273, 274], and interactive architecture [45, 50]. These interfaces have integrated active shape-changing materials [21, 28, 36, 45, 50, 60, 79, 158, 220, 234, 241, 254, 274], passive responsive materials [103, 203, 204], mechanical or structural mechanisms [8, 114, 133, 181], and phase-changing actuation [202]. The interfaces have been made through sewing [28, 38, 50, 124, 135, 149, 158, 234, 274], felting [21], weaving [36, 220], and knitting [8, 79, 80, 88, 103, 204, 254, 284].

Knitting has been uniquely favored not only for shape-changing effects but also for sensing and protection [228] due to its structural conformity. Continuous interlocking loops result in interfaces that have considerable stretch, enhancing knit fabric's ability to serve as *input sensors* [14, 148, 172, 176, 185, 252]. For instance, Ou *et al.* [172] presented a machine-knit resistance-changing elastic stretch sensor. Despite insufficient accuracy in reading, Wijesiriwardana *et al.* [252] developed knitted resistive transducers, as well as wearable electrodes and solenoids. Paradiso *et al.* [176] integrated machine-knitted piezoresistive sensors into a garment, insulating the components using a tubular intarsia technique.

Output shape-shifting effects have also been explored through knit structures. Oftentimes enabled by SMA wire, prior works devised knitted interfaces that bloom into different shapes [88], shrink to fit the user [80], generate compression [79], and balloon out in firefighting suits [284]. Alternatively, inlaying "tendons" in stuffed knit structures [8] have demonstrated a range of 3-dimensional mechanical movements.

Unique to our approach is the use of shape-changing knitted textiles for generating *haptic sensation.* While many works have explored the use of textiles for visual shape-change [8, 21], limited work has explored textiles which generate haptic feedback. Granberry *et al.* knitted with SMA wires; however, the resulting deformation only serves to assist with self-fitting. Whether the knit generated force is sufficient for haptic feedback remains unspecified.

Our work uniquely integrates SMA with everyday yarns to render four different types of tactile information. We identify diverse shape-changing effects that range in strength from powerful enough to shift the skin and subtle enough to tickle the surface of the skin. These shape-changing effects can be applied to a variety of body locations because of versatile knit structures.

4.3.2 *Wearable Tactile Interfaces*

Haptic feedback devices deliver mechano-tactile stimulation, which the skin's sensory receptors can detect. However, a significant limitation of current devices is the lack of seamless and versatile form factors that can deliver mechano-tactile stimuli to various body locations. Prior literature presented device stimuli including (1) compression, (2) skin-stretch, and (3) brushing, yet often in bulky forms. *KnitDermis* examines multiple body locations with diverse skin topography and conformity.

4.3.2.1 *Compression (Squeezing).*

In prior work, compression is often used interchangeably with squeezing. In strictly technical terms, the mechanical forces that constitute compression and squeeze do not wholly overlap. However, in this paper, we focus on the physical effects of the two. Pure compression leverages evenly concentrated radial force directed inward while squeezing consists of tangential force in addition to inward force. Compression is often generated from pneumatics [93, 184, 269, 279], servo-motors [39, 42, 216], or SMAs [11, 69, 83, 99, 265], sometimes in knitted fashion [80]. A study [182] uses servo motors and vibrotactors to deliver squeezing and vibration, achieving a purely radial force and eliminating vibration transfer. However, servo actuators are bulky, challenging to extend to diverse body locations, and limit subtle feedback. Gupta *et al.* [83] uses the contractile force of SMAs to create a tangential force for a squeezing effect. However, the narrow surface area might not offer optimal tactile feedback for spatial compression, and the uninsulated SMA poses safety hazards. He *et al.* [93] devised multi-chambers to segregate normal (radial) forces which deliver tapping, holding, and tracing. However, each module's aggregated volume and the accompanying pump takes up an area twice as big as the interface, disincentivizing applications. Few devices discussed here accommodate body locations other than wrist or forearm due to miniaturization challenges.

4.3.2.2 *Skin Stretching.*

When an end-effector travels on the skin exerting shear force, it stimulates low-threshold receptors that detect skin deflection and warmth (i.e., Ruffini endings) [132]. The shear force generates skin-stretch sensations that can be perceived as dragging, pinching, or twisting, depending on how the interface is attached to the skin. Simones *et al.* [209] applies shear force to the skin by having SMA deform a polylactic acid (PLA) structure that is either attached or tightly fastened to the skin. The device is capable of rendering pinch, squeeze, and twist stimuli on the forearm. However, PLA modules afford little skin conformity, thus preclude complex skin topographies from their potential use. On the other hand, Springlets [11] takes advantage of silicon and rubber to reduce the interface's profile to 3mm, enhancing skin conformity. The interface adheres to six different body locations, exerting shear force for pinching and dragging. Nonetheless, "bias force" is engineered only for the convex body part. Meli *et al.* [150] looks into a two-belt bracelet where each belt can be pulled by coherent or opposing directions to apply shear force. Again, the accompanied servo actuator and the linear actuator expose the device to noisy and obtrusive feedback and are only compatible with a reasonably expansive area like the forearm. To provide rich VR experiences, Gong *et al.* [77] leverages compressed air to exert a lateral force on the forearm, generating linear displacement of the device itself. However, reliance on large air cartridges and the trade-off between force and size of pneumatics limit applicability. Other interfaces [77, 269] excite mechanoreceptors by controlling how the tactor travels. Ion *et al.* [106] applies both shear and normal force by controlling the tactor. However, the rigid housing that encases motors mounts only on the forearm. Likewise, Yoshida *et al.* [269] offers multimodal tactile sensations using a hybrid tactor but its bulky housing limits its application to locations lying flat on the ground.

4.3.2.3 *Brushing.*

Unlike other stimuli, light touch, such as brushing, excites different skin receptors than pressure-sensitive ones [198]. Knoop *et al.* [122] devised tactile bars to laterally move against the skin while a belt stabilizes the device. Strasnick *et al.* [218] uses multiple foam brushes coupled with DC motors, where precise calibration of the distance between the brushes and skin is sought to avoid dragging.

The devices above take advantage of skin receptors to generate a wide range of stimuli. However, they all lack versatile and slim form factors that can be applied to diverse body locations, which this work contributes.

4.3.3 *On-Body Interfaces*

The field of on-body interfaces is of great relevance to our study. Motivated by substrates with a slim profile and active materials with high energy density, on-body interfaces have a distinguished form factor from electro-mechanical haptic devices. Advanced material science research on micro-thin film based interfaces [19, 117] has led to the birth of skin-like circuitry. However, the applications are bridled by high cost. On the other hand, film-based interfaces in HCI have proven their superior conformity that does not disrupt tactile acuity [168]. The film-based interfaces in HCI have extensively utilized skin as an input space through capacitive sensing [112, 138, 169, 248, 249]. Given the micro-scale thickness, these interfaces have utilized gold leaf [112], lamination [144], laser-patterning [248], real-time drawing using a stylus [187], screen-printing [138, 169, 249, 257], inkjet printing [167], and printed polymeric conductive ink [249, 257] which maintain minimal thickness. More recently, 3D printing onto fabric to induce passive shape-change for on-body sensing [78] has also been proposed. Sensing systems have also been explored through IMUs [111, 144] and strain sensors [138]. For visual outputs, thermochromic pigments [112, 113, 224, 244] have been favored. Kao *et al.* have presented stiffness change as an output [110]. For vibro-tactile outputs, Withana *et al.* [257] integrated electrodes and polymeric conductive ink into tattoo substrate layers. Despite their high energy efficiency, the bandwidth of tactile output is bound by vibro-tactile signals. Another work has used ferroelectric electroactive polymer for self-sensing and outputting vibration [268]. Nonetheless, beyond the foregoing outputs, the materials encased in the thin films do not possess force sufficient for dynamic tactile stimulation.

Of higher relevance to our study are pliable substrates that output tactile sensations through *deformation*. Springlets [11] has presented a set of layer-based substrates housing SMA to generate tactile displays through deformation. However, the interfaces showed little examination of the distribution of the outputs onto challenging body locations such as joints or concave body locations, leaving many body topographies unexplored. SMA wire has also been used to deform modular patches [157] to generate shear force. However, modules did not explore body topography other than the forearm. By knitting SMA wires Granberry *et al.* proposed a proof-of-concept garment to generate compression through large contraction [79]. A woven I/O interface with SMA embedded offered haptic feedback [224] through deformation. However, neither distribution of the feedback nor skin-conformity to extreme body locations was examined. An application for haptic rendering was envisioned through 3D printed modules on fabric to maneuver a movement through SMA [151]. KnitDermis delves into the mechanics of shape-changes and drives dynamic tactile outputs through deformation of the interface. Departing from film-centric form factors, the knitted substrates we present illuminate integrated knit structures as a core tool for conformable tactile interfaces.

4.4 BACKGROUND

Here we provide an overview to the HCI community on the key concepts in machine knitting used in this work.

Machine Knitting Overview. Knitting forms a fabric which can be likened as a two dimensional piece of plane from a yarn which equals to one-dimensional line, by looping the yarn continuously into rows and columns. Our work leverages industrial machine knitting, which can generate structures and textures not afforded by hand knitting. Industrial knitting machines can be broadly categorized as weft-based knitting or warp-based knitting, drawing metaphorically from the "warp" (vertical) and "weft" (horizontal) directions in weaving. This paper works with weft knitting, in which fabric is formed by continuous "stitch loops" built row by row. For a comprehensive overview of machine knitting, please refer to Underwood's thesis [236] and Narayanan *et al.*'s excellent glossary [161].

Knitting as a Shaping Tool. In this paper we specifically leverage knit stitch structures for sculpting substrates in two and three dimensions which can better conform to the body. Tactile actuators are inlaid in the substrates for haptic feedback. The key advantages we exploit include knitting's *shaping capabilities* as well as the ability to create *freeform integrated channels*:

- Knitting's *shaping capabilities* are enabled by manipulating the basic unit of the "stitch loop." By transferring the stitches we can shape a flat sheet into free-form 2D sheets. By transferring *groups of stitches* in bigger steps, one can add volume to the sheet. More complex composites can be achieved by combining two or more structures together. The differentials in the neighboring structure result in the structure of a dome or saddle.

- Forming *freeform integrated channels* is another advantage unique to knitting that is challenging to achieve by other fabrication methods. Numerous techniques in knitting inform ways to compose channels that vary in design and rigidity. The knitted channels are soft and can be inlaid with active materials, which produce deformation for tactile stimulation.

4.5 DESIGN FACTORS FOR MACHINE KNITTED TACTILE INTERFACES

We implemented KnitDermis interfaces as knitted on-body overlays which are soft and slim. Embedded with SMA micro-springs in knitted channels, the soft form enables them to be worn on diverse body locations. Here we introduce the main design factors: *(1) tactile actuation mechanism*, *(2) materials*, and *(3) knit structures* for generating KnitDermis interfaces (Figure 12).

4.5.1 *Tactile Actuation Design Factors*

4.5.1.1 *Actuation Mechanism and Design (Figure 12(a))*

Our approach is based on using SMA micro-springs that contract when activated. We embed the SMA micro-springs into channels in the knitted on-body overlays (i.e., the "substrates").

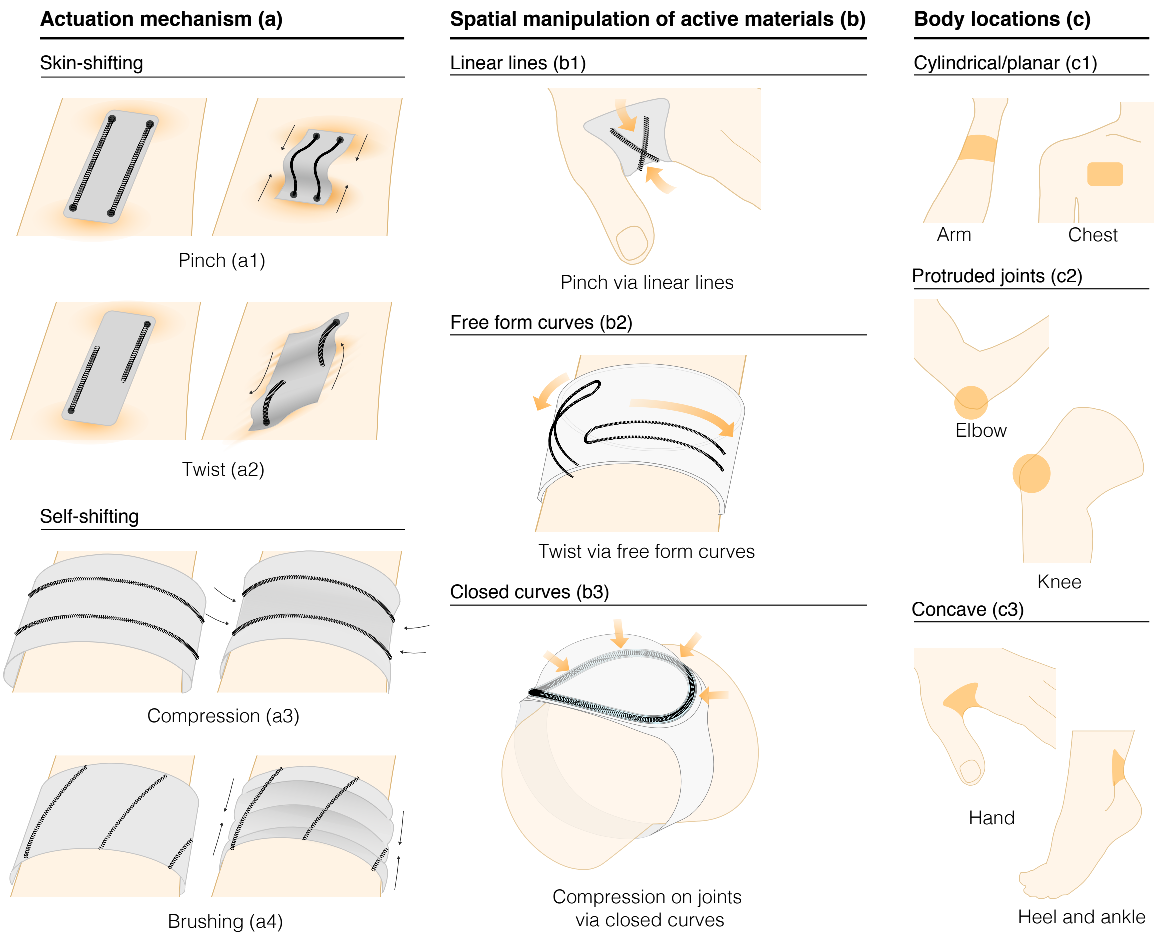

Figure 12: The main design factors for KnitDermis interfaces consist of actuation mechanism (a), spatial manipulation of SMA (b), and body location (c). Actuation is achieved either through shifting the skin in various directions (a1-2) or morphing the interface itself radially (a3) and longitudinally (a4). More specific design of haptic feedback is enabled by shaping SMA (b). A set of crossing linear lines can yield different forces depending on the skin area in contact (b1). Open free form curves can be used to enlarge the skin area being affected (b2). Closed curves can work in concert with underlying skin geometry (b3). By altering parameters (length, curvature, or distance) of SMA placement, haptic sensation can be fine tuned. KnitDermis can be applied on a variety of unexplored body locations such as cylindrical or planar spots (c1), protruded spots (c2), and concave spots (c3).

When current flows through the SMA micro-springs, they contract and become shorter, shifting the knitted channels. When selected areas of the substrate are attached to the skin, the corresponding skin regions become shifted, and for example, can result in the pinching sensation depicted in Figure 12(a1). Another design option is for the knitted substrate to be close to, but *not attached* to the skin. In this case, the substrate can deform itself when activated, and for example, generate a compression sensation as depicted in Figure 12(a3). Based on the substrate attachment (or non-attachment) to the skin, we identify two techniques that are realized by ***skin**-shifting actuators* and ***self**-shifting actuators*:

- **Skin-shifting actuators.** When the substrate is attached to the skin, the SMA shifts the contacting skin regions while it contracts. In this case, we design SMA micro-springs to contract in either opposing or identical directions. Actuation in identical directions results in the pulling of the skin region to a converging point, giving a *pinching* sensation (Figure 12(a1)). On the contrary, the actuation in the opposing directions leads to wringing of the skin, resulting in a *twisting* sensation (Figure 12(a2)).
- **Self-shifting actuators.** When the substrate is not attached to the skin, the actuation of the SMA can deform the interface itself, resulting in circumferential or lateral contraction of the interface. Circumferential contraction results in a *compression* sensation (Figure 12(a3)), and lateral contraction results in a *brushing* sensation through the "scrunching" of the substrate (Figure 12(a4)).

4.5.1.2 *Spatial Manipulation of Active Materials for Tactile Feedback (Figure 12(b))*

The tactile feedback can be further customized through intentional design of the spatial distribution of active materials (i.e., SMA micro-springs) throughout the knitted substrate, which are threaded into the knitted channels. Knitted channels afford high degrees of freedom for integrating active materials. Channels can be constructed in linear lines (Figure 12(b1)), free-form curves (Figure 12(b2)), or closed curves (Figure 12(b3)). Multiple channels intersect or traverse the structure independently. By having the channels constructed within the knit structure, the force generated by the SMA micro-spring is transmitted to the shape of channels, displacing them in tandem with SMA movement.

4.5.1.3 *Skin Topographies (Figure 12(c))*

Tactile feedback can also be customized according to the underlying skin topography or body landmark [58, 249]. While tactile interfaces in HCI have focused placement on *planar* (e.g., back of hand) or *cylindrical* (e.g, forearm) body locations (Figure 12(c1)), KnitDermis interfaces explore challenging topographies such as *protruded body joints* (Figure 12(c2)) and *concave* *(hollow) body locations* (Figure 12(c3)). Protruded body joints (e.g., elbow, knees, and knuckles) can serve as "blocking barriers" that offset the force being applied against the skin. With the band type substrates, for instance, these protruded landmarks can receive both tangential force from the actuation and the radial force from the compression of the bands. On the other hand, concave (hollow, curving inward) body locations (e.g., the purlicue [the concave space between the thumb and index finger], armpit, and Achilles tendon arch) require substrates that can conform to steep curvatures, which we can uniquely realize through machine knitting.

4.5.2 *Material Related Design Factors*

Here we detail the material-related design decisions important to the design of KnitDermis interfaces.

4.5.2.1 *Active Materials: SMA micro-springs*

KnitDermis takes advantage of miniaturized SMA for discreet form factors. We have compared both SMA wires and SMA springs from different manufacturers, whose external diameter did not exceed 2mm. We began from a SMA wire (diameter: 0.152mm, Fort Waynes Metal, 33°C) which was extremely pliable and could be threaded into the knit substrate with ease. However, the wire failed to perform sufficient strain to deform the knitted substrate. Under the same condition, a SMA spring (diameter: 0.40mm, Toki Coporation, transition temperature unspecified) was tested, which resulted in excessive contraction and also scorched the substrate. To meet our needs for an adequate amount of contraction and a transition temperature close to the body temperature, we landed on a SMA micro-spring (internal diameter: 0.5mm, Kellogg Research Labs, 45°C). The material provided sufficient yet moderate force, maintained the perceived temperature around 38°C (averaged through measurements from thermal camera) and was pliable enough to be integrated into channels.

4.5.2.2 *Substrate Material: Mechanical Property of Yarns*

The choice of yarn affects the general stretchability of the substrate. During numerous iterations, non-ideal yarn combinations were the primary cause of failed prototypes. An elastic yarn mixed with a chunky yarn would result in an excessively stiff substrate for SMA to exert force. Conversely, choosing fine yarns without reinforcement would result in prototypes too compliant to control the actuation of SMA micro-springs. To avoid further failures, frictional, flexural, and tensile properties of yarns have been considered in constructing knitted channels. Tensile property and the weight of yarns are critical determinants for an effective actuation. For instance, heavier yarns impose weight across the substrate, which will in turn obstruct the actuation. Yarns with extreme elasticity, again, such as Sting (83% nylon, 17% Spandex, Silk City), add stretch and increase the stiffness of the resting substrate, which also hinders SMA micro-springs from deforming the substrate. Along with the yarn diameter, fiber type plays an important factor in heat conductivity. We observed little difference across fiber types we tested (nylon, viscose, and modal) on heat transfer. Instead, there was greater association between heat transfer and the diameter of the yarn. Given the transition temperature of 45°C, we concluded that yarn counts between 70 and 90 tex provide sufficient insulation and comfortable temperature range. We used Puma Stretch (80% Viscose, 20% Elite, Silk City) and Jaguar (85% Modal, 15% Nylon, Silk City) for most of the substrates. For the substrates that needed more stretch, we added one end of Sting to Jaguar.

4.5.2.3 *Non-SMA Inlay Materials*

The constructed knitted channels are capable of accommodating an indefinite list of materials, as long as they are pliable enough to pass through the channels. Inlay materials can be embedded within channels to constrain, counterbalance, or accelerate the actuation of SMA micro-springs. For instance, temperature-dependent conductive materials that do not respond to thermal stimuli could be used to connect two or more SMA micro-springs without intensifying the actuation. Passive springs could be integrated to counter-balance the actuation to restore SMA micro-springs to their original state. Lastly, inlay materials could also include

Ni-Cr wires to boost heat transfer to SMA springs. Within the scope of this paper our test of inlay materials did not go beyond inactive conductive materials.

4.5.3 *Knit Structure Design Factors*

Here we elaborate on the key machine knitting structures (Figure 13(a)) we leveraged for generating KnitDermis devices, which are central to our form factor design.

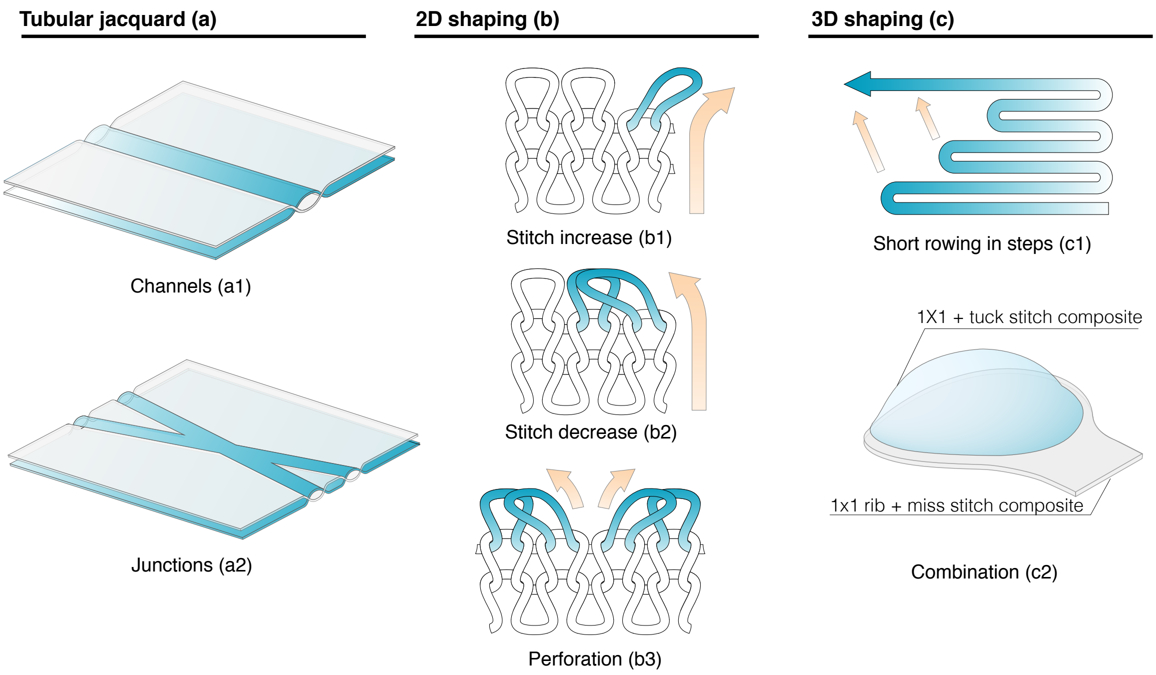

Figure 13: A catalogue of knit structures adopted by KnitDermis. Tubular jacquard (a) is used to encase active and passive materials. With complete freedom in size and shape, tubular jacquard can create channels to accommodate yarn-like materials (a1), let materials cross each other (a2) or create a pocket to accommodate larger components. By manipulating stitches (b) KnitDermis' interfaces can contour body topography (b1-2). Modifying the stitches can also perforate the substrate to connect the materials to power source or other components (b3). Volumetric shaping can be achieved through skipping a section of needles for "short rows" (c1) or combining heterogeneous structures (c2).

4.5.3.1 *Knitting Free-form Integrated Channels Through **Tubular Jacquard** (Figure 13(a))*

Tubular Jacquard is a jacquard technique where a two-color composition is knitted in double system alternating between the front and back bed. If one yarn is stitched on the technical front, the other yarn knits on the technical back. This alternation of stitches creates tubular pockets between the two layers, which can be manipulated depth-wise (z-axis) and width length-wise (x- and y-axes) to construct a variety of channels. The tubular spaces are not limited in shape, therefore they can also serve as a pocket or accommodate materials of different sizes. In this paper, variations of the technique have been used to create channels and junctions where different materials cross paths (Figure 13(a2)). Otherwise, we refashioned the structure with alternating stitches along the edges of the channels to preempt the inlay material from deviating from the channels.

4.5.3.2 *Knitting for challenging body locations through **2D Shaping** (Figure 13(b))*

Transfer stitches can be used to increase (Figure 13(b1)) and decrease (Figure 13(b2)) the number of stitches in a row thereby changing the shape of the form factor. Transferring stitches to adjacent needles on both selvages (the left and right edges of a piece of knitting) is the most common way to create 2-dimensional shaping. Stitch transfer can be used to gradually shape a substrate into a variety of profiles depending upon the number of stitches transferred per row as well as the frequency of the transfers. Transferring on both selvedges while varying the frequency of transfers from every row to every other row and then back to every row will result in an hour-glass shape. This is useful when generating knit substrates for concave body locations (i.e., the steep curve on the purlicue [the muscle between the thumb and index finger] and the Achilles heel). For purposes outside of shaping, transfer stitches can be adopted to create a perforation in the substrate for incorporating the micro-spring (Figure 13(b3)).

4.5.3.3 *Knitting for convex body locations through **3D Shaping** (Figure 13(c))*

Short rowing is a 3D shaping technique in which one isolates a section of needles (rather than the entire bed of needles) for knitting (Figure 13(c1)). When *short rowing* is done in a stepped fashion, it can be used to create shaped forms as well as raised 3D volumes. *Combining structures* is an alternative way to employ 3D shaping. Shifting from one knit structure to another within the same substrate is a subtle approach to shaping (Figure 13(c2)). The differentials in abutting structures or stitches can conspicuously elevate the fabric in 3D (e.g., *links* structure). For cases where the interface covers the joint, *short rowing* and *combining structures* can build volume to accommodate the protruded body locations. *Short rowing* can be used to create domes encircled by tubular structures for SMA actuation. To shape larger areas into a dome, we customized a composite of tuck and miss stitches, which condenses and expands specific areas. The differentials in the density of the structures raised the area to form larger domes.

4.6 knitdermis fabrication

Step 1. Sketching. We start by profiling specific body locations (according to Section 4.5.1.3 Skin Topography) as planar/cylindrical (e.g., forearm and wrist), protruded joint (e.g., knuckles, elbow, and knee), or convex (e.g., hollow between thumb and index finger, Archilles heel arch).

These profiles inform (1) the knit structures, (2) the force and actuation characteristics, and (3) the attachment of the interfaces. Substrates with cylindrical profiles can be designed to exert either tangential force along the circumference or shear force to a partial area of the cylinder. Skin profiles work in tandem with actuation mechanisms (Section 4.5.1.1 Tactile Actuation Mechanisms) when determining the stimulus of interest. Some skin profiles may fit better to certain stimuli or actuation mechanism, but not to others. For instance, the concave muscle on the hand will pose difficulties for the *brushing* or *self-shifting* mechanism to be performed effectively. Given this location is more suitable for *skin-shifting*, one may choose a stimulus that can be presented through *skin-shifting* and decide on the areas to be attached.

Step 2. Fabrication.

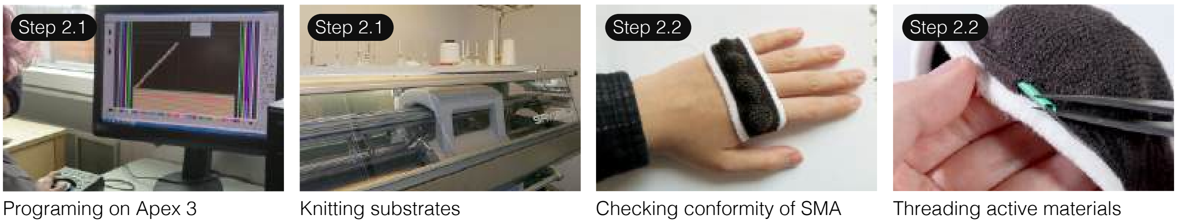

Figure 14: Step 2. Fabrication process of KnitDermis. Designs of KnitDermis substrates are digitally programmed on Apex 3. Once knitted with desired yarns and appropriate stitch cam setting, substrates are placed on body to see if they conform to underlying body geometry and the SMA is placed fittingly. Prior to threading active materials, soft and pliant tubes are inserted first to protect substrates.

Step 2.1. Program knit substrate. Our KnitDermis substrates are fabricated on the SRY 123 SHIMA SEIKI digital knitting machine. With the profiles and desired actuation in mind from the previous step, we now program our designs on the Apex 3 software which is fed into the SRY 123 SHIMA SEIKI knitting machine. Once programmed, the software translates the design into a machine-readable file. Central to Apex programming are (1) the construction of channels, (2) the composing of knit structures, and (3) the shaping of the substrate (Figure 13). Programmed channels can form closed or open curves and can intersect to embed SMA micro-springs into desired patterns. Channels can be programmed to vary in width: we can create larger chambers to accommodate electrical connectors, or alternatively reduced in width to encase thinner wires. If a substrate consists of other non-SMA inlay materials (as described in Section 4.5.2.3 Non-SMA Inlay Materials.), alteration to channels can be carried out here.

Configuring knit structures on Apex software plays an integral role, especially for the topographies that profile protrusion or complex geometries. Depending on the topography, we segment a substrate into different knit structures. For instance, to conform to protruded joints (e.g., knees and elbows), we program a substrate to have denser knit structures next to looser structures, to induce the interior of the substrate to balloon out (see Section 4.5.3.3 3D Shaping). Knit structures play a significant role in controlling the stretchability of a substrate. We discriminate areas that undergo frequent movements from those that are stationary, and program them with more elastic knit structures (such as tuck stitches), while the rest is programmed with a rigid structure. The resulting substrate can thus withstand kinematic movements and be firmly stabilized on the skin.

The last step on the Apex software is to shape the substrates in order to effectively conform to the desired areas. The free form substrates enabled by the software allow one to attach the devices to more complex body locations.

Step 2.2. Threading SMA & connecting to hardware. Once the substrates are knitted, we place them on body to see if the locations of SMA conform to targeted body topographies. With successful substrates, the final step of fabrication is threading SMA micro-springs and other inlay materials into the channels. Prior to threading SMA, we insert soft tubes first to preempt damaging channels inside the substrates. Due to the gauge of the substrate or yarn properties, programmed channels could vary by substrate causing difficulties in threading. In this stage, we adjust settings of the machine and modify Apex programs to re-calibrate channels. After the SMA micro-springs are successfully threaded, we connect the springs to a custom designed circuit board for actuation.

Step 3. Application on the body.

Device attachment varies based on the actuation mechanism (see Section 4.5.1.1 Tactile Actuation Mechanisms). *Skin-shifting actuators* which typically involve shear force and give receptors an illusion of skin being stretched, require the substrates to be attached on the skin. It is critical to have those substrate regions attached to the skin maintain a certain distance apart, based on the two point discrimination threshold (a minimum distance for two points to be discerned as two distinct points) in prior haptic literature [237]. In order to simulate twisting, the two discrete regions that move in opposite directions require a distance beyond 3.42cm (right forearm 3.28cm) [237]. For pinching substrates that were designed for the purlicue of the hand and for the Achilles heel arch, we dispersed the two discrete regions by more than 1.27cm and 2.09cm, respectively, based on the prior studies [125, 237]. Once the minimum distance between the two discrete areas has been decided, we used medical grade skin tape (MIILYE Double Sided Skin Tape) to attach the interface to the discrete regions.

On the other hand, *self-shifting actuators* with substrates exerting compression and brushing adopt "band-type" form factors (e.g., wristbands, kneebands). Band-type form factors preclude the interfaces from additional adhesives. Stretch in the substrates holds them close to the skin.

4.7 KNITDERMIS CASE STUDIES

Based on the aforementioned fabrication approach and multi-faced design factors, here we present eight case studies which encompass diverse body locations, actuation mechanisms, and spatial patterning of SMA micro-springs. Generated through our research through design [71, 282] methodology, these case studies uncover rich design potential of knitted tactile on-body interfaces by illustrating adaptability to a variety of body locations without losing compliant property.

These case studies have been derived from numerous design iterations where the knitted structures were enhanced to provide optimal tactile feedback. Figure 15 shows the implementation of eight interfaces that convey four different stimuli — compression, pinch, twist, and brushing — on the skin.

Figure 15: Summary of eight KnitDermis case studies. Depending on haptic feedback of interest, each case study variously configures design factors to conform to specific body locations. *B-wrist* and *C-wrist* adopt *self-shifting* mechanism whereas the remainder utilizes *skin-shifting* mechanism.

Compression wristband (C-wrist). In this case study, we present a substrate that simulates a sense of compression. Designed to fit along the circumference of the wrist, the substrate includes two free form channels, embedded with two SMA micro-springs. The two channels intersect with each other, a feature made possible through the tubular jacquard knit structure. Tubular jacquard is a double knit structure that produces two-color designs. The design is knit on the technical front of the fabric while the reverse of the design is knit on the technical back. With KnitDermis, tubular jacquard serves the primary role of creating free-form tubular chambers that can accommodate various inlay materials. Here we adapt tubular jacquard, and contain it to a series of single stitches so the structure no longer works as a chamber, but encloses the channels to prevent the micro-springs from straying.

Compression knuckle band (C-knuckle). Here we explore a substrate that leverages hand knuckles as a blocking barrier. We present a knit structure that is comprised of three distinct types of sub-structures: integrated channels, an array of four knuckle pads, and the strap of the band. Precise placement of the knit substrate is critical for achieving effective control of the actuation against the knuckles. With an excessively forceful actuation, the micro-springs would not be stopped by the protruded topography. We construct two channels to contour the knuckles, which do not come in contact. The micro-springs move tangentially to contract along the contour of the knuckles in concert with a moderate degree of radial compression of the band which pushes the channels down. The shrinkage of the contoured channels under the compression of the band delivers a sensation precisely aimed at the protruded topography. To conform to the knuckles, we sculpted volumes for the four knuckle pads through short rowing. The structures then shifted to tubular and formed two channels that flow along the contour. We added a strand of Sting yarn (83% Nylon, 17% Spandex, Silk City), which provides stretch to the substrate.

Compression knee band (C-knee). This case study takes advantage of both the compressing force of the band and tangential movement of the SMA micro-spring. The substrate configures three sub-structures: the channel, the customized protruded pad, and the strap of the band. The channel accommodates a strand of SMA micro-spring that contours the patella (i.e., the knee cap). To cover the expansive protrusion (the "dome") of the knee, we customize our own knit structure by adding tuck stitches, which push out the fabric creating a spherical space. We construct a channel that encircles the knee "dome" using tubular knitting. Building upon the tubular channel, we modified part of the structure for a small hole (Figure 13(b3)) that connects to the channel. The hole provides more ease of threading SMA micro-springs into the channel. A composite structure of 1x1 rib and miss stitches are used within the strap to compress the width and increase stretch.

Compression elbow band (C-elbow). In a similar configuration to the knee band, this case study presents three distinct sub-structures: the channel, the customized elbow pad, and the strap. We use tubular knitting for the channel construction. However, for the customized pad, we have modified the center by adding tuck stitches in order to create more space for comfort. The tuck stitches push out the material forming a rounded shape to fit the elbow.

Pinching patch for the hand (P-hand). Our pinching mechanism works by attaching the edges of the knit substrate to the skin. The embedded SMA micro-springs then shift the attached regions directly. This approach presents an illusion of directional movement by moving two discrete regions of the skin at the same time. The substrate attaches to two regions of the skin: one on the dorsal and the other on the palmar aspect of the hand. To accommodate the concave structure that connects the index finger and the thumb, we shaped (Figure 13(b)) the substrate into curved selvedges. The channels cross each other to be consistent with the shape of the substrate. The knit substrate mirrors an hour-glass shape, with wider edges for skin attachment, and a slimmer middle section for fitting to the area between the index finger and thumb. Accordingly, the intersecting micro-springs present greater actuation on the edges than the middle section of the substrate. Tubular jacquard (Figure 13(a2)) was the primary structure used in fabricating this case study. We minimized the stiffness by precluding yarns with high tensile force.

Pinching patch for the heel (P-heel). Here we extend the previous case study to accommodate another under-explored skin topography with similar features, the Archilles tendon arch, which is the convex area located above the heel. Based on the topographical attributes of this body location, the constructed substrate consists of an elongated bridge and wider edges for attachment to the skin enabled by active shaping (Figure 13b). The integrated free form channels correspond to the shape by contouring the selvedges, which are connected by inactive channels that carry conductive wires. Similar to the previous case study, we chose yarns with less tensile force as the substrate does not require high stretch but instead requires pliability.

Twisting band for the wrist (T-wrist). If the pinching mechanism pulls the attached regions together to a fixed point, the twisting mechanism pulls the attached regions away in opposite directions. Based on the commonly accepted two point discrimination distance for the forearm [125, 237], we first specify two discrete regions within the substrate that are more than 4cm apart. We then attach the regions to the skin. The substrate moves concurrently with the SMA actuation. Constructed through tubular jacquard, the two U-shape channels contract in opposite directions toward crimp connectors, shifting the attached skin in different directions. Similar to the aforementioned band type substrates, we select yarns which enhance stretching to generate light compression.

Brushing band for the wrist (B-wrist). Our last case study explores a brushing sensation. The substrate does not need to be attached to the skin. Instead, the substrate itself deforms, shrinking closer to the skin in a lateral movement. Its *self-shifting* movement creates a subtle sensation without applying steady pressure, which delivers light and rapid excitation to skin receptors [253]. Our unique approach is enabled by the parallel positioning of four micro-springs that are evenly spaced out.

For the yarns, we choose ones with minimal tensile force which allow for a looser stitch setting to minimize stiffness.

Microcontroller platform of KnitDermis interfaces. We implemented a 28mm × 28mm custom printed circuit board (PCB) based on the ATmega328P microcontroller. The MCU uses pulse-width modulation (PWM) to control 4 N-channel MOSFETs in dual package (IRF8313PBF), which corresponds to the maximum of 4 SMA springs in the prototypes. The components were selected to accommodate the SMA with the shortest length, i.e., lowest resistance and thus highest current. The actuation time and speed were tuned by adjusting the PWM duration and duty cycle for each prototype. A 4-position slide switch configures the MCU to output the unique preprogrammed actuation pattern for each prototype. A 3.7V, 1000mAh LiPo battery powered the PCB during the user study (described in following section). Side entry JST connectors were used for a robust and flexible connection between the PCB and SMAs.

4.8 EVALUATION

We conducted a study to understand (1) the effectiveness and wearability of KnitDermis interfaces worn on the body, and (2) user perceptions and envisioned applications. To uncover these aspects, we conducted a within-subjects experiment with the eight KnitDermis interfaces presented in the case study section which encompass four types of stimuli: compression, pinch, twist, and brushing. We then used these interfaces as a *material probe* [109, 238] for a semi-structured interview in which participants reflected on the interfaces in relation to existing objects, and envisioned how the interfaces could be integrated into their everyday lives [55].

4.8.1 *Method*

4.8.1.1 *Participants & Apparatus.*

Eight volunteers participated (4 females, 4 males, ages 18–50 years). The eight interfaces presented in the case study section were administered for each participant in the study: four interfaces deliver a compression sensation (for the knuckles, wrist, elbow, and knee body locations, respectively), two deliver a pinching sensation (for the hand and heel locations), and one each for twist and brushing (both for the wrist).

4.8.1.2 *Study Protocol.*

Our study consisted of (1) a pre-survey, (2) a functional experiment phase, and (3) a material probe semi-structured interview phase.

(1) Pre-survey (10 minutes). Participants were asked to complete a pre-survey a week prior to the study, which included a questionnaire covering demographic data and body dimension measurements of their forearm, knee, and elbow for preparing appropriately-sized apparatus. Regardless of the sizing, the functionality of the interfaces remain uniform across all participants. The sizes were referred solely for adjusting inactive part (e.g., straps) of the knee, elbow and knuckle bands, leaving the rest of the configuration uniform.

(2) Functional experiment phase (60 minutes). The study started with the participant viewing a 4-min introductory video prepared by the researchers on the four types of stimulus: *compression, pinch, twist*, and *brushing*. The researchers then asked the participants to wear and attach interfaces on their own (adhering to COVID-19 IRB protocols), without being made aware of which type of actuator stimuli they wore, where the SMA in the prototype was embedded, or that a unique stimulus would be supplied in each interface. The participant was given an instruction manual to consult how to wear the interfaces. After the participant wore the interface, they were asked to move their body around to ensure it was adhered properly.

Each interface was administered for three cycles. In each cycle, the researcher triggered the actuator via pressing a button on a custom designed PCB. The participant was made aware of when to expect the cycle as the PCB blinked three times before the actuation. The participant was then asked to classify the stimulus type (options are compression, pinch, brushing, and twist) and to rate the stimulus' noticeability and the actuator's comfort. Once the responses were logged, the researcher reset the SMA by relaxing it. This was repeated in the three cycles. A short post-prototype interview was administered where the participant was asked to describe how the stimuli felt in their own words. The participant had a 2-minute break to remove any lingering effect from the prototype before resuming the study. This sequence was repeated to cover all eight interfaces.

Overall, the experiment was administered *8 participants* $\times$ *8 prototype interfaces* $\times$ *3 cycles* = 192 trials. Evaluation of *discriminability, noticeability*, and *user comfort* ensued after each trial. For *discriminability*, the participant distinguished the stimulus from *compression, pinch, twist, or brushing*. For *noticeability* and *user comfort*, the participant evaluated the stimulus on a 1 to 7 scale (Very unnoticeable (1) – Very noticeable (7); Very uncomfortable (1) – Very comfortable (7)).

(3) Material probe semi-structured interview phase (30 minutes). After the functional experiment phase, the eight prototypes were placed on the table to serve as *material probes* [109, 238] for the participant to touch, wear, and engage with. A semi-structured session was conducted where the participants were asked to select interfaces they could see themselves using in everyday life, and to explain at length how they would design/wear the interfaces and interact with it. We also asked participants to compare and contrast the system with alternatives which might serve similar functions, such as wearable devices, clothing, or accessories.

4.8.1.3 *Analysis.*

Our experiment involved factors `interface` {*C-wrist, C-knuckle, C-knee, C-elbow, P-hand, P-heel, T-wrist, B-wrist*}, and `stimulus_type` {*compression, pinch, twist, brushing*}. Eight `participant_ids` were created with another factor `gender`. During the functional experiment phase, no data point was removed since there were no unexpected failure or detachment of the device. For the response variables, `noticeability` and `comfort`, we took account of the uniqueness in the `interface` through linear mixed model [91, 255]. Statistical analyses were performed to identify the relationship between the `interface` and response variables. Fixed effects of the model were `interface` and `gender` while `participant_id` were regarded as random effects. Visual inspection through histogram and scatter plot did not reveal any deviations from normality and homogeneous variance of residuals. Multiple pair-wise comparisons were obtained from the Tukey post-hoc analysis. We obtained p-value by likelihood ratio tests of the full model with the effect of interest against the model without the effect of interest. For *discriminability*, we visualized the descriptive data by `stimulus_type` and `interface`. Statistical analyses were performed using R [190] and *lme4* [18].

For semi-structured interview, audio recordings were manually transcribed to identify salient themes. All qualitative data in the post-study interview underwent iterative coding by two experienced researchers. All of the authors discussed the meaning of the text to identify common themes. We used codes with a reasonable degree of agreement to identify salient themes based on thematic analysis [240].

4.8.2 *Functional Experiment Study Results*

In the functionality study phase, we sought to answer three questions: (1) Can KnitDermis interfaces be worn *comfortably* on diverse body locations? (2) Can KnitDermis interfaces deliver *noticeable* tactile sensations on the skin? (3) Can the wearer *distinguish* the different tactile outputs delivered by the interfaces?

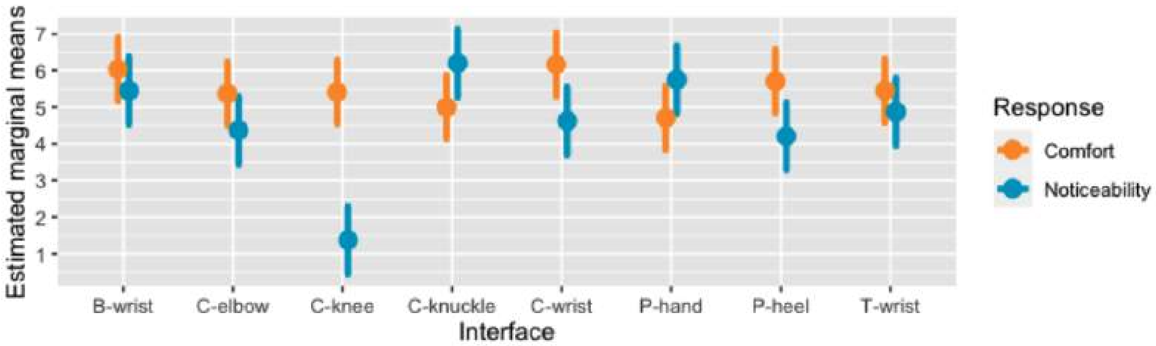

Figure 16: Estimated marginal means of interfaces, in comfort and noticeability (95% CI).

4.8.2.1 *Comfort.*

It was rated high with a global average of $M = 5.48$ ($SD = 1.20$). For `comfort` by `interface` the highest rating, on average, was obtained by *C-wrist* with $M = 6.17$ ($SD = 1.04$), whereas the lowest was obtained by *P-hand* with $M = 4.71$ ($SD = 1.56$). `Comfort` by `stimulus_type`, revealed that its highest rating was obtained by *brushing* with $M = 6.04$ ($SD = 1.23$), whereas the lowest was obtained by *pinch* with $M = 5.21$ ($SD = 1.38$).

Takeaway: Can KnitDermis interfaces be worn comfortably on challenging body locations? Yes, the participants were positive about the comfort of the interfaces. Regardless of the stimuli, participants overall referred to the interfaces as "extremely soft" and the actuation "pleasant." Feedback towards *P-hand* was more varied: some participants (P3, P8) found the placement to be "unusual," while others (P1, P6) found it comfortable and "interesting."

4.8.2.2 *Noticeability.*

On a global average, `noticeability` was rated $M = 4.61$ ($SD = 1.84$), leaning toward the positive. `Noticeability` by `interface`, on average showed the highest rating at *C-knuckle* with $M = 6.20$ ($SD = 0.62$) whereas the lowest was at *C-knee* with $M = 1.37$ ($SD = 0.33$). `Noticeability` by `stimulus_type`, on the other hand, showed the highest rating at *brushing* with $M = 5.45$ ($SD = 1.47$) with the lowest rated at *compression* with $M = 4.14$ ($SD = 2.11$).

Consistent with the distinct with-in subjects tendency (Figure 16), our model revealed a significant main effect of `interface` on `noticeability` ($\chi^2(7) = 62.48$, p-value $< .001$). We used Tukey post-hoc analysis to compare all `interface` pairs. The pair-wise analysis revealed a significant disparity between *C-knee* and the rest of 7 `interfaces` pairs (p-values $< .01$).

Takeaway: Can KnitDermis interfaces deliver noticeable tactile sensations on the skin? Yes, more with certain interfaces than others. For most participants, the interview response aligned with the data. The three *C-knuckle, P-hand, B-wrist* with the highest `noticeability` rates, received responses of being "very noticeable."

In contrast, *C-knee* was illustrated as a "light touch."

Some participants (P2, P6) attributed the reduced sensation to the body location, asking, "it's on the knee bone, probably not many receptors there?".

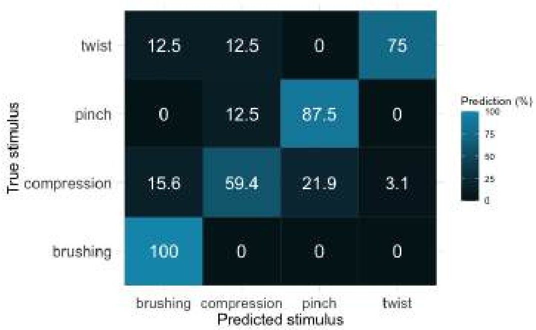

Figure 17: Discriminability rates by stimulus types.

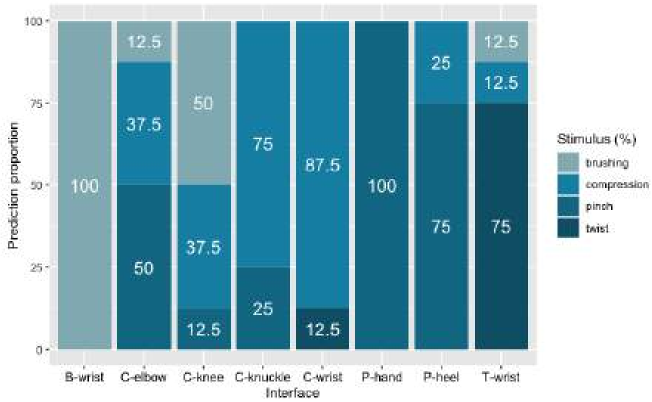

Figure 18: Discriminability rates by prototypes.

4.8.2.3 *Discriminability.*

Some tactile stimuli we sought to present were viable only on specific body locations (i.e., brushing can not be performed on the hand). To address the resulting imbalance in the `stimulus_type` we used a normalized prediction matrix (Figure 17).

The matrix shows that the participants predicted the *brushing* most accurately, obtaining 100% prediction, followed by *pinch* (87.5%), *twist* (75%), and *compression* (59.4%). Relative frequency histogram (Figure 18) revealed the prediction rate by `interface`. *B-wrist* and *P-hand* achieved 100% prediction rate. Following the two, *T-wrist* and *P-heel* achieved 75% of predictability. *C-knee* was more likely to be confused with *brushing*, while *C-elbow* was also more likely to be confused with *pinch*. The *compression* devices worn on joints, *C-knee* and

C-elbow, bore lower prediction rate than *C-wrist* and *C-knuckle* worn on the forearm and hand. While *pinch* devices showed overall high prediction rates, *P-heel* rated lower than the other.

Takeaway: Can wearers distinguish the different tactile outputs delivered by KnitDermis interfaces? Yes, more accurately for some interfaces than the others. The post-stimuli short-interview questions (administered after each prototype) supported the data. Commonly specified characteristic of *B-wrist* was the directional shift of the sensation. Several participants (P5, P6, P7, P8) described it as a "directional touch" that was "moving to a [designated] point." *P-hand* was frequently noted for distinguishable direction of the areas being pulled. P6 added, "two different sides (of the device) brought it together". Our result shares the same inquiry with prior findings [2], which underscore body location as a critical factor of tactile sensitivity. Our result also extends the discussion on extra parameters in designing haptic feedback [276] by differentiating duration, contact area, and intensity of feedback.

4.8.3 *Material Probe Phase Semi-Structured Interview Findings*

We situate the KnitDermis interfaces as *material probes* [55, 109, 238] to understand: (1) What formulates one's perceptions of knitted tactile interfaces? As a novel interface, KnitDermis lacks pre-existing associations. How do participants perceive the interface with regards to existing objects, experiences, and representations?; (2) What are the envisioned usage and applications of the interface?

4.8.3.1 *Perceived Associations and Representations of KnitDermis Interfaces.*

Form: Device versus Close-Body Clothing. Participants tended to base their experience with KnitDermis interfaces in comparison to smartwatch and wristbands, which also cover a designated part of the body (P1–P7). However, they were also quick to point out differences: KnitDermis devices were described as more “soft” (P5), “natural” (P3), and “familiar” (P4) in comparison to commercial wearable devices, particularly due to their rich texture which resembled clothing. The soft and close proximity of the KnitDermis interface to the body led participants to find it resembling hosiery, leggings, and undergarments (P4, P5, P8). P5 described how KnitDermis interfaces were “very intimate and close to the body,” and P8 described "a sense of safety" when wearing the interfaces. P6 described how the devices "enveloped your body" when activated and projected a sense of "fullness."

Actuation: Organic, life-like interfaces. Participants also commented on the actuation of the KnitDermis interfaces which provided a more "gradual" stimulation in comparison to vibration from smartphones/watches which were described as more "robotic" (P6). The gradual nature of the actuation led to descriptions of the interface being "animated" (P2) and also "having a mind of its own" (P6). Other life-like descriptors include P6 and P7 who compared the device to a "caterpillar" and P8 who described them as being "soft and friendly."

4.8.3.2 *Envisioned Usage and Applications of KnitDermis Interfaces*

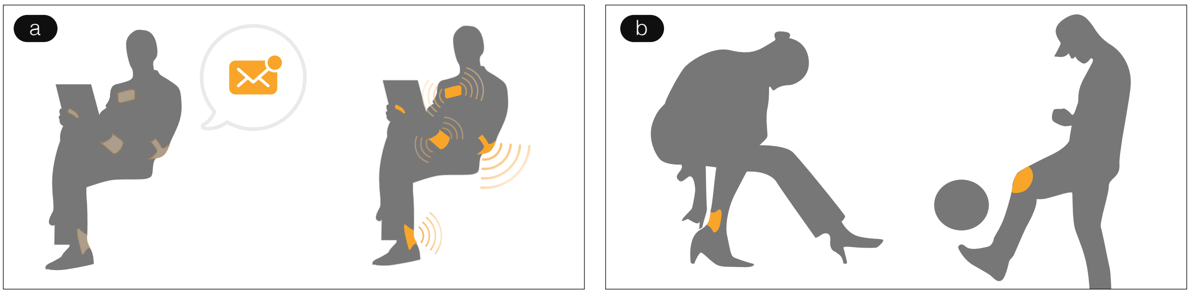

Figure 19: Envisioned use cases for KnitDermis. Participants described how KnitDermis could be worn on diverse body locations for distributed on-body notifications (a). Participants envisioned integrating KnitDermis into their everyday clothing for haptic feedback or dynamic protection (b).

A Protective "Third Skin" for Physical and Sports Therapy. Participants described the gradual actuation of the devices to be therapeutic (P8) and also to provide "a sense of security" (P5). P2 envisioned physical therapy applications for posture adjustment, such as having a larger scale KnitDermis interface along the spine. Other participants envisioned the interfaces providing massage for stress relief (P5, P7), treatment of muscle atrophy (P6), and combining twisting and compression sensations for an integrated massage suit (P8). The interfaces were also viewed as "smart medical tape" that one could wrap around their hands and sensitive body joints for protection when engaging in sports such as boxing or lacrosse (P6, P8). P8 further described wearing the interface as "making a shell for our bodies," which he compared and contrasted with fictional superhero Iron Man's rigid armor. He described KnitDermis protective "third skin" – a soft armor more conformable to the skin.

Distributed On-Body Notifications. Participants discussed how the distribution of the interfaces across diverse body locations enabled "different parts of [their] body to communicate [to them]" (P3). They discussed how it would be feasible to have distributed notifications on body locations under-explored by previous wearable devices. Out of all the eight notifications offered by the prototypes, the compression knuckle band (prototype *C-knuckle*, preferred by P1, P2, P4, P5, P8) and the pinching patch for the hand (prototype *P-hand*, preferred by P1, P4, P5) were favored by several participants due to their unique placements. P3 further discussed at length assigning different notifications to different body locations: "if I get a compression on my knee, it means it's time to go out for a run; if I get a pinch on the forearm, it means I received an urgent message ." P4 envisioned a long sleeve with distinct function for each section of the arm. P6 envisioned "coding information into the different compression or expansion" as a way to distinguish the phone calls he received. Other body locations participants preferred included the back of the ear (P2), neck (P5), the shoulder (P7), and body locations without joints, such as the chest (P3) and the back along the spine (P7, P8).

An Intimate Personal Interface. The soft and close proximity of the KnitDermis interface to the body led participants to find it resembling hosiery, leggings, and undergarments (P4, P5, P8). Several participants envisioned wearing the interface underneath everyday clothing (P3, P4, P8), and to have it serve as a "private" interface (P4, P8) that is designed "only for themselves" (P3).

P3 preferred to have it as a "personal" device that served as a "warning system" for private physiological signals instead of wearing it at public body locations. P1 envisioned the use case where the interface gives you a "hint" during meetings without others noticing. Similarly, P8 envisioned the interface as a "private notifier" unlike a phone which can be visible to others. P1 viewed the interface as a representation of remote loved ones – they could feel a squeeze when loved ones wished to communicate with them.

Integrating Active Elements into Existing Garments. While the KnitDermis interfaces are designed as on-body overlays for specific body locations, participants envisioned a wide range of possibilities around how they could be integrated into everyday clothing. P1 and P5 envisioned integrating the *P-heel* into a sock. P3 and P4 described having distinct haptic sensations integrated throughout a long sleeve. Similarly, P6 mentioned incorporating compression sensations into the cuff regions of shirts, especially where a separate band is sewn on or where the sleeve is turned back. For these envisioned applications, participants mentioned the importance for the actuation of the interfaces to be distinct from the typical compression or texture felt when wearing clothing (P2), and also designing for washability (P2) of the interfaces.

4.8.3.3 *Reflections*

Here, we reflect on observations from the results of our semi-structured interview.

Shifting from more "robotic" to "life-like" stimuli for close-body tactile interfaces. Participants' perceptions of the KnitDermis interfaces revealed a desire for fabric-based actuators to function differently from the tactile output from smartphones or watch-based devices. We observe that participants felt conflicted about having more "robotic" haptic output so close to their bodies and felt that the soft and textured properties and gradual actuation of the interfaces fit better when worn close to the skin. The desire for slow, gradual transitions mirror findings by Devendorf *et al.* [55], in which gradually shifting thermochromic clothing displays were preferred over digital screens. Moreover, the gradual actuation of the KnitDermis interfaces also led to perceptions of it seeming "life-like" and "having a mind of its own." This shares similarities with Kao *et al.*'s [114] study of mobile on-body robots, which were viewed as personal companions, pets, or even bugs. For KnitDermis interfaces, the metaphors were less form factor driven, but centered on how the gradual actuation resembled being touched or stroked by another person or living being. Our observations may offer insight for designers in considering a more expressive palette of tactile sensations when designing close-body interfaces.

A new, intimate layer for wearables for "backstage" presentations of self. We observe how participants desired wearing the KnitDermis interfaces *underneath* clothing – a location not commonly occupied by wearable devices. In the everyday fashion wardrobe, we typically dress in "layers" (e.g., from the inner underclothing layer, to the "socially appropriate" shirts, pants, and accessory layer, to the outer coat layer). However, current wearable devices often are limited to the "layer" of accessory-based form factors (e.g., smartwatch). We reflect on how KnitDermis interfaces are perceived as more "intimate" devices than current mobile and wearable devices, presenting opportunities to occupy a new "layer" in the wearable ecosystem that supports more personal applications.

Further, drawing inspiration from Goffman's theory [76] of front and back stages in social interaction, we observe that KnitDermis interfaces have the potential to support expressive and enchanting "backstage" presentations of self [76] in public settings. Using theatrical metaphors, Goffman defines the "front stage" as where individuals are in front of an "audience" and where the desired self is presented. The "backstage," on the other hand, is a private and hidden space where people can be themselves without maintaining an ideal self-image. Current wearable devices already support many "front stage" applications for work and productivity. The intimate layer occupied by KnitDermis could open up a new design space for *designing for enchantment* [147] through applications such as personal communication with close ones, and therapeutic feedback for stress relief.

4.9 DISCUSSION, LIMITATIONS, AND FUTURE WORK

Improvements for and Opportunities of the Knit-based Approach. While machine knitting allows KnitDermis to meet many aspects that are integral to compliant on-body interfaces, its fabrication process should be improved to expedite iterative fabrication and foster effortless inter-disciplinary collaborations. With current technology, it is not possible to precisely estimate substrates' actual sizes at the programming stage. It would be only after knitting a substrate with selected yarns first and measuring its gauge to scale the program that one would be able to produce the substrate in desired dimensions. It could be worthy of developing a simple knit simulation program that informs estimated dimensions to accelerate fabrication. The slim profile of KnitDermis substrates requires extra attention while threading in SMA micro-springs. While we have knitted holes (Figure 13(b3)) for easier threading, threading SMA springs has to be preceded by inserting soft tubes (Figure 14). For future opportunities, using water soluble yarns to knit inner channels, which can be dissolved in water once SMA springs are threaded, could offer a time-saving way to streamline the process.

Aesthetic Customization Opportunities. Participants expressed broad interest in the aesthetic aspects of KnitDermis. Patterns were one of the aspects that captivated participants. Patterns helped participants locate the SMA micro-springs, as highly discreet integration disabled them from visually locating the SMA without touching the interfaces. Once recognizing the presence of the micro-springs through patterns, participants made efforts to predict the stimulus. Participants were also enthusiastic about changing the patterns in their favor and wished to have bolder patterns for special occasions. Interest in the color scheme of KnitDermis was also shared, with participants suggesting if KnitDermis mirrors their preference or outfit, it could serve a more expressive role as a hybrid accessory. It could be worthwhile to investigate the role of aesthetic customization and how it may affect the wearer's social acceptance in our future work.

Software Design Tool to Support a Fully Integrated Workflow for Interdisciplinary Collaboration. It is critical for KnitDermis interfaces to be designed with precise fit to contour body topologies. Further, the patterning of SMA micro-springs needs to be intentional for optimal effect. The prototypes in the paper were *crafted* for each body location through multiple rounds of iterations to achieve desired fit and tactile feedback. Again, it could be worthwhile to streamline this process through a front-end software design and simulation tool which can account for parameters from body location, tactile actuation, to yarn texture and output a design file readable by digital machine knitting software.

Such a tool could also benefit interdisciplinary collaboration between textile experts and HCI researchers. Digital machine knitting software can have a high barrier to entry for HCI researchers, while textile experts may find SMA challenging to control as a new material. A software tool could translate and lower the barrier for collaboration and ideation between the two fields.

Improving Actuation and Control of SMA. Currently, the SMA micro-spring used in this paper cannot recover to its pre-actuation state without prior thermal training of the material. Once actuated, the substrate requires manual intervention to restore from the actuated state. These constraints have led to failures in retaining a homogeneous magnitude of actuation across trials. In a few instances, where short lengths of micro-springs were in use, failure for complete recovery seems to have affected perceived sensation, with participants reporting decreases in accuracy score towards the third trial. Some interfaces have proposed other ways to reverse the shape, such as leveraging the contrasting force of the skin [86] or the use of passive springs. However, to troubleshoot inconsistent actuation, monitoring the post-actuation state of SMA is unavoidable.

While the current KnitDermis system controls the current flowing into the spring through PWM, more rigorous controls can be executed through a closed-loop feedback system which further regulate cooling and heating rate for consistent, repeatable actuation strain. Beyond electrical measures, improving the reversibility of SMA could be attempted during the fabrication process. For instance, if adding "springy" spacer yarns between the layers could allow sufficient restorative force for the micro-springs to retrieve original shape, we could anticipate some degree of reversible actuation. Considering SMA composite to alter mechanical properties [175] at a yarn level could provide a workaround. Finally, enabling multiple heterogeneous behaviors in one micro-spring through thermal cycling [16], could be pondered upon for more delicate rendering of haptic feedback.

Towards Even Slimmer Form Factors. KnitDermis contributes to body conformable interfaces with a portable controller. However, tubular jacquard provides freedom in channel construction at the expense of thickness due to inherent double-layers. It also limits assigning different yarns to desired areas. Alternatively, modified version of "short rowing" could reduce the structure to a single layer. "Pin-tucks" could also differentiate yarns and help KnitDermis achieve minimal thickness. In addition to altering knit structures, exploring finer yarns, such as silk, or monofilaments with appropriate tensile force could follow. Finally, composing a self-contained interface including a PCB that can be embedded in the interface with conductive wires, will be a necessary step to improve the portability of KnitDermis.

4.10 CONCLUSION

We presented KnitDermis, on-body interfaces that deliver expressive tactile feedback on the skin surface.

We conducted a research-through-design investigation on the rich structural capabilities offered by machine knitting for embedding SMA micro-springs in knitted channels and conforming to challenging body locations through 2D and 3D shaping techniques. We have presented the actuation mechanism, manifold design factors, and fabrication approach to create the interfaces. We present a series of case studies which encompass diverse body locations, actuation mechanisms, and spatial patterning of SMA micro-springs to convey four different stimuli — compression, pinch, twist, and brushing — on the skin. Our user study experiment demonstrates the effectiveness and comfort of KnitDermis interfaces worn on a range of body locations. Our semi-structured interviews highlight how the gradual movement of the interfaces made them feel "life-like" and "intimate." We reflect on design opportunities for enchanting and personal applications through the intimate wearable layer occupied by KnitDermis. By bridging the realms of textile knitting and haptic interfaces, we shed light on the rich opportunities for knitting as a *soft* approach for crafting expressive, enchanting, and novel tactile interfaces.

4.11 POSITIONING KNITDERMIS WITHIN THE DESIGN SPACE

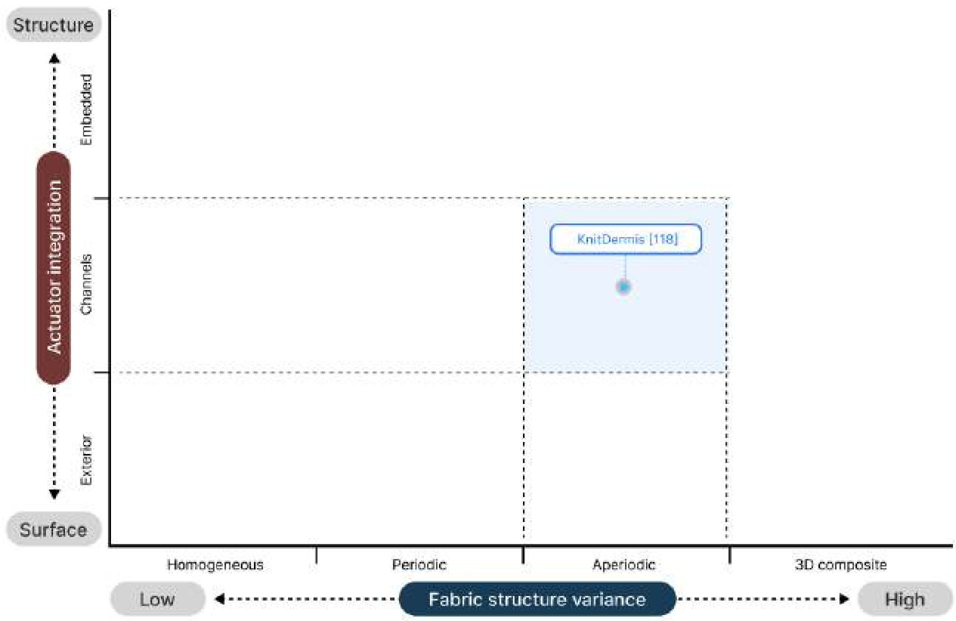

Figure 20: Situating KnitDermis in the design space.

KnitDermis is characterized by its unique geometric adaptation, achieved through the incorporation of *aperiodic* combination of constituent structures, while integrating nitinol actuators in fabric *channels* (Figure 20). These 3D structures enable the device to mold precisely to the contours of designated body parts, such as elbows, knuckles, and hands, ensuring a snug and comfortable fit. The actuators, integrated into various 2D and 3D geometries, create deformations that conform to the body, eliciting tactile responses.

5

ROBOTIC TEXTILES FOR ON-BODY LOCOMOTION

5.1 KNITSKIN: MACHINE-KNITTED SCALED SKIN FOR LOCOMOTION

This chapter builds on the published work KnitSkin, which is designed to adapt to a specific area of the forearm while conforming to its contours. This conformal quality is crucial, as the device is intended to facilitate movement rather than remaining static at a specific body location.

In the previous chapter, this thesis explored how a static device can be fabricated to be conformal through aperiodic knit structures. This chapter introduces KnitSkin, featuring a structural variation designed to infuse surface roughness through periodically arranged knit structures. This arrangement creates anisotropic friction, which is crucial for propelling the device forward when combined with linear actuation. The periodic knit structures not only enhance surface texture but also enable directional friction, allowing the device to move more efficiently across surfaces.

In this context, this work is situated within the *periodic* scale of the *fabric substrate* parameter in the design space, exploring the *channels* to integrate bulkier pneumatic actuators without affecting the flexibility of fabric substrates.

A team consisting of myself, Shreyas Dilip Patil, Sarina Matson, and Melissa Conroy, all from Cornell University, was involved in the creation of the KnitSkin device, under the guidance of Cindy Hsin-Liu Kao. Throughout this chapter, I will use "we" to denote our collaborative work in developing the device. KnitSkin, as presented in this thesis, is based on the paper of which I am the primary author. The paper is entitled "KnitSkin: Machine-Knitted Scaled Skin for Locomotion." and was published in ACM CHI 2022 [119].

5.2 INTRODUCTION

While interactive devices in Human-Computer Interaction (HCI) have typically been static or fixed in one location, there has been increased interest in *mobile* devices which can change their locations. This includes a range of on-body robots [52, 53, 56, 114], which can climb on clothing, as well as locomotion and swarm robots [130, 225] which can travel on flat ground and vertical surfaces. However, little research has investigated mechanisms for climbing on *cylindrical surfaces*. Cylindrical terrains, such as the forearm at the wearable scale to pipes, lamp posts, and tree branches at the environmental scale, are widely situated in our daily lives. Mobile robots which can climb on these various cylindrical terrain have the potential to yield new applications for health rehabilitation, industrial monitoring, to urban and agricultural robots. A prime challenge has been a compliant robot form factor that can conform to the geometry of a cylindrical surface while propelling upward.

We introduce KnitSkin, an entirely soft and coordinated system that can climb up underexplored *cylindrical surfaces*. Embodied in a sleeve, the coordinated locomotion system is composed of pneumatic actuators that dominate propulsion and a conformable substrate that exhibits different frictional values according to the directions. The substrate can integrate a comprehensive range of actuators in a minimally intrusive manner. Taking inspiration from limbless locomotion, often seen in earthworms and leeches, the actuators linearly extend to enable global propulsion of the sleeve. The flexible substrate accommodates local movements of the actuators and translates them into a globally coordinated locomotion. Mimicking the skin of certain limbless terrestrial organisms such as the scale of pythons and "setae" of earthworms, the substrate features tunable attributes such as frictional “scales” to direct movement and bolster propulsion. Particularly prominent in KnitSkin is a simple and universal locomotion strategy: the form factor that lets locomotion defy gravity by providing normalized force, yet accommodating dynamic movements. With computationally tunable structures, KnitSkin enjoys the freedom of integrating diverse actuators regardless of mechanism, orientation and shapes. The resulting KnitSkin sleeve can crawl on cylindrical surfaces with an ability to passively adapt to terrain variations without active control.

In this paper, we introduce the fabrication and mechanical parameters of the knit substrates. We then evaluate the performance of KnitSkin in which locomotion is expressed as a function of different attributes of the substrate parameters and terrain.

Drawing from the results, we present various applications in which KnitSkin is envisioned in a wide range of scales serving various purposes. By enabling locomotion using soft fabrication methods, we present a novel mode of traversal that can extend to the human body, pipes or arboreal environments. Our contributions include:

- We introduce computational knitting and linear extension as a locomotion strategy to generate a sleeve-like soft robot which can traverse an uncharted class of terrain: cylindrical surfaces. Our soft approach is compatible with a variety of terrain attributes: material, slope, and curvature.
- We characterize material and geometric attributes of the knit substrate with regard to anisotropic friction. We evaluate terrain variations as main determinants for locomotion. In evaluating the locomotion, we investigate: (1) the impact of terrain materials, (2) the effect of the number of actuators on locomotion efficiency, and (3) the impact of terrain attributes such as slope and curvature on locomotion.
- Building upon the results, we introduce applications of KnitSkin encompassing a variety of scales and surfaces, ranging from the human body, industrial pipes to arboreal environments.

5.3 BACKGROUND AND RELATED WORK

5.3.1 *Bio-inspired Locomotion*

Locomotion strategies in nature adopt a wide range of mechanical tactics to traverse a variety of extreme spaces. Modeling after nature, attempts in robotics to navigate various uneven surfaces [108, 121, 189, 270] and confined spaces [44, 81] have been enabled by hardware that mimics frogs, geckos, cockroaches, or ivy vines.

For instance, frog feet have inspired robotic suction cups [270] which can climb walls while consuming low energy. Gecko's sticky pads have led to the development of adhesive appendages [156] which assist robots to climb vertically and turn at 90 degree surfaces. The body motion and compressibility of cockroaches have been studied in legged robots to mimic rapid locomotion in crevices. Likewise, plants offer inspirations that are unique to their growth-based navigation. For example, vines have inspired a variety of robots that can navigate congested and confined spaces [44, 81, 90, 259, 260].

Nonetheless, designed for on-ground operation, the technologies are not known to be compatible with cylindrical surfaces, and nor have they been evaluated with different terrain attributes.

Most relevant to this research is the locomotion in limbless organisms such as snakes, earthworm and caterpillars. Due to the absence of appendages to support dynamic motion, these organisms have evolved to make the best use of skin and muscle. Their skins stretch and shrink synchronously with the muscle movement, which aids or hinders the body to protrude forward. For instance, earthworms present "setae" on their skins which anchors the animal in the soil and prevents backsliding. The same is true for scales in snakes. Taking inspiration from snake scales, studies [191] explained how adding a skin of stretchable kirigami could help soft actuators crawl. Likewise, the segmentation of muscle in leeches, inchworms and caterpaillars have inspired a range of soft robots [30, 57, 227, 235]. Professed as terrestrial locomotion, few advances in locomotion technology in the robotic field are scalable or applicable to cylindrical terrains. As an exception, Agharese *et al.* [3] developed a vine-inspired robot that wraps around the human arm for haptic feedback. However, the tip-extending strategy is far from the notion of *mobile* interface. Taking inspiration from nature, KnitSkin takes broad attributes of cylindrical terrain into account, laying the groundwork for scalable applications from relocatable wearable interfaces to industrial and agricultural robots.

5.3.2 *Deformable Fabric-based interfaces*

Methods to animate fabric-based interfaces have been extensively studied in HCI.

Different actuation mechanisms have been developed to stimulate the shape-changing effects, which can be categorized into *structural* and *local* deformation. *Structural deformation* through yarn or fiber has been enabled chiefly by knitting engineered materials into the fabric [103, 203, 204]. Integration of the materials prompts global deformation for applications in garment compression [80], heat insulation [284], or even artistic expression [220]. However, with known demerits of insufficient force, irreversibility, and lack of local tunability, such applications have yet to be used for performing locomotion on the human body.

Local deformation, on the other hand, enjoys a wider variety of mechanisms from SMA, bi-layer, to pneumatics. Inducing shape-change through SMA has been welcomed thanks to the material's compliant and compact form factor. Contrasted with the earlier bracket, the material is now enclosed into local parts of the interface through sewing or couching [38, 158, 273, 274], weaving [224], 3d printing [151] or layering [11]. Some applications encompass specific purposes from donning and doffing assistance [135], meditation [70], hypotension treatment [79], to autistic spectrum therapy [60]. Other applications of SMA serve a range of on-body haptic applications [11, 69, 83, 118, 224] or rather all-around purpose [151]. Despite the prominent uses in creating local transformation, SMA has not been popularized for locomotion due to its lack of sufficient force for propulsion and irreversibility. Alternatively, shape-change of fabrics can also be achieved by stacking materials with dissimilar responsiveness to stimuli. Deformation through such bi-layer compositions enjoys more complaint materials, such as films [263] and polymer [195]. Transformation takes place as the differential of responsive and inert materials modulates expansion and contraction. While shape change through bi-morph has proven to be rapid and precise, it has not been adopted for locomotion applications due to insufficient force and slow recovery. Overcoming the lack of force and slow actuation cycle, more controlled shape change is yielded by combining pneumatics and fabrics. In many studies, soft pneumatics' ability to bend, extend, and rotate are enfolded by stretchable knitted fabrics to exhibit anisotropic properties to preciesly control motion. Resulting structures translate pressure into a variety of motions, lending themselves to effective tools for rehabilitation [47, 163–166, 178, 192, 210, 215]. Nevertheless, few pneumatic-based applications have sought purposes beyond rehabilitation. While serving a different purpose from KnitSkin, the versatile use of knits in conjunction with soft pneumatics inspires our investigations. The stretchability that is unique to knit textiles and no other fabric structures is an important enabling technology for KnitSkin's locomotion.On the whole, an ample history of fabric-based shape change has demonstrated extensive utility and compatibility with various materials. However, despite its ability to embrace diverse materials and actuators, deformable fabrics have yet to be used for locomotion technologies, to which this work aims to contribute.

5.3.3 *Wearable Robots for Locomotion*

Wearable robots, which explore an alternative terrain to tabletop surfaces [130, 225], bring locomotion onto the human body. While some robots assist with body-location specific tasks, such as on-body fabrication [40] or kinematic movement [145, 272], others are mobile and exhibit maneuverability on clothes or skin. While early work has centered on the engineering facets of cloth-climbing robots [37, 73, 137], recent work has also demonstrated HCI applications [52, 53, 114]. Rovables and KINO use magnetic wheels to climb clothes, demonstrating applications from pervasive healthcare, remote communication, to fashion expression. While cloth-climbing robots have enabled new interaction possibilities, attempts to move directly on skin remain limited. Epidermal Robots [52] uses a skin-suction mechanism embedded in a legged robot to grasp and move up the skin surface. However, the hardware-centric approach suffers from challenges such as sagging of skin and unreliable cup-skin seal on curved body locations. Designed for the arm, Movelet [56] is a motor-driven bracelet that can move up and down the arm for haptic feedback. However, the weight of the device and reliance on adhesive tape enable only a limited position of arm.

KnitSkin explores a "soft" approach for locomotion, especially taking advantage of knit substrates which have demonstrated conformability not only to curved and challenging body locations [118], but even to diverse terrains in natural [68] and man-made environments [64, 65].

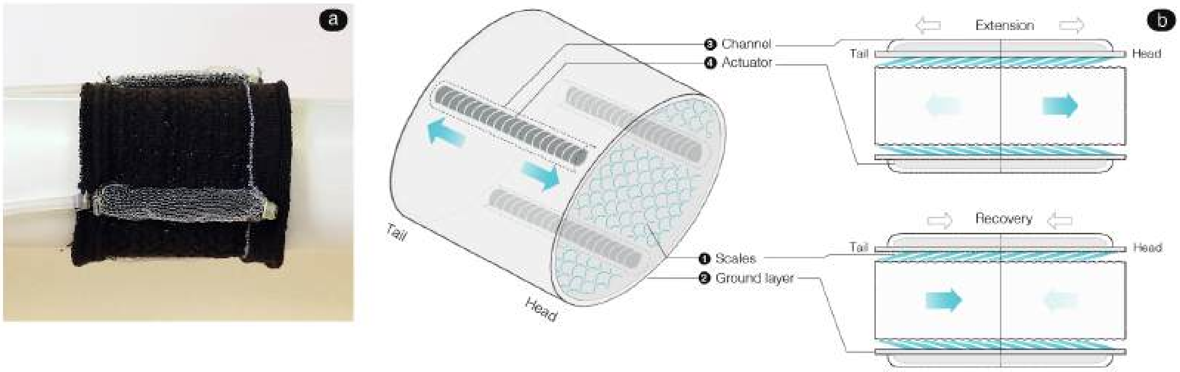

Figure 21: KnitSkin composition. (a) The resulting sleeve, which configures three channels with pleated actuators enclosed. The scales are knitted on the inside. (b) The mechanics of propulsion: during extension, the scales on the side of the head slide forward while the ones on the tail interlock with the surface. During recovery the scales on the tail propel while the ones on the head anchor on the surface.

5.4 KNITSKIN

The overarching principle of KnitSkin's crawling motion lies in linear extension-recovery and interfacial friction between the knit substrate and underlying surface (Figure 21). KnitSkin adopts actuators and encloses them in channels to obtain local extension. Leveraging flexibility in the knit substrate, the local extension is in turn transferred globally, elongating the entire KnitSkin structure longitudinally. Here we identify design elements of KnitSkin and their role in delivering coordinated locomotion.

5.4.1 *Producing Knit Substrates for Frictional Anisotropy*

The knit substrates are fabricated on a digital v-bed knitting machine, SRY 123 SHIMA SEIKI. The knit substrates play two primary roles in KnitSkin: (1) affording frictional anisotropy and (2) serving as an enclosure for actuators. Anisotropy is a property of having directional dependency. In this paper, we pursue *frictional anisotropy*, which means the knit substrate will produce the least resistance when being pushed towards a certain direction. Frictional anisotropy is also a widespread mechanism behind many natural creatures: snake skin [262], bur-cladded plant [23] or hairy legs of insects [23], and other animals [17]. Depending on the direction of movement, angled protrusions slide smoothly or ratchet the contacting surface [66]. To develop frictional anisotropy, we have engineered a novel knit structure that marries yarns with conflicting characteristics: stiffness and elasticity. We also take advantage of the vertical progression of knit in which a row knits first followed by another to form a texture in a stacked manner. KnitSkin's substrate is composed of three features: *a ground layer*, *scales* and *channels*.

Yarns with elastic properties form the *ground layer* while yarns with high stiffness and less elasticity form the *scales*. The *channels* can be knitted with any of the two yarns. The *ground layer* knits on the needles forming regular knit loops whereas the *scales* skip the needles, leaving the yarn run freely on the back of the *ground layer* (Figure 22 (c)) As the *scales* knit on the same row, the new *scales* on the following row stacks on to the earlier ones, creating a stepped texture. While knitting on the machine, the *ground* yarn is put under tension as it is being stretched to knit on needles that are apart. Once the knit structure is released from the needle bed, the stress built up in the *ground layer* lets the entire structure including the *scales* draw in. This shrinkage is larger along the rows than columns, affecting a great amount of lateral flexing of *scales*(Figure 22(c)). An adequate amount of elasticity in the *ground layer* and the stiffness in the *scales* is crucial, as the balance between them determines the angled orientation of *scales* (Figure 22 (a), (b)). For instance, if the *scale* yarn exhibits little stiffness as in Figure 22 (b), it is prone to scales with negligible curve. We elaborate on each feature of the substrate below:

- **Scales**: The size, pattern, density and roughness of the *scales* can be tuned with few constraints as long as the elasticity of the *ground layer* and the stiffness of the *scales* strike a good balance. For instance, the size of *scales* can be tuned by letting the *scales* skip more needles (Figure 23 (a)-(c)). By arraying *scales* in straight columns such that no adjacent *scales* are pressing them down one can expect lofty *scales*, whereas by patterning the *scales* so they imbricate one can obtain low-rise *scales* (Figure 23 (d)-(f)). Likewise changes in the density (Figure 23 (g)-(i)) and the roughness of the *scales* can contribute to the anisotropic properties of the substrate. We identify detailed geometric and material parameters of the *scales* and characterize resulting anisotropic effect in later sections.

- **Ground layer**: The role of the *ground* is to withstand a certain amount of stress during knitting. When released from the needle bed, the *ground* pulls in the *scales* laterally. The

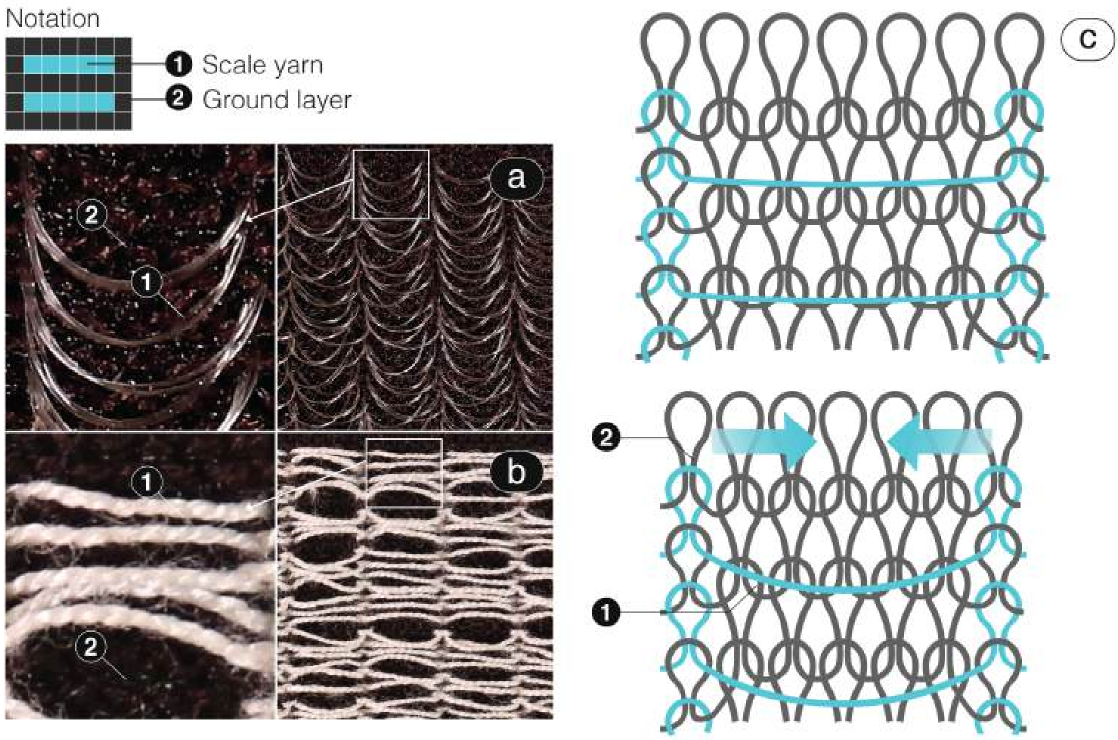

Figure 22: Knit structure to form a scaled substrate. The notation indicates that five needles are skipped to form a scale. (a) Illustrates when the scales consist nylon monofilament. The stiffness of monofilament induces the curve as the ground layer draws in. In contrast, scales in (b) show negligible curves due to the lack of stiffness in the yarn. The scales are straightened up, causing no "stepped" texture.

limited elasticity in *ground* yarns could result in little retraction, which in turn leads to *scales* that are less curved. When the *scales* are straightened up (not curved), they no longer stack onto each other losing the stepped texture. One can dampen the amount of pull-in by combining less elastic yarns with elastic ones or enhance the extent of pull-in by knitting with multiple elastic yarns.

- **Channels**: To enclose a wider variety of actuators, we extend the tubular jacquard structure that has been demonstrated by Kim *et al.* [118]. The structure creates pouches in various shapes and dimensions, however wide or thin. By altering tubular jacquard, substrates can accommodate different numbers of actuators in different shapes. *Channels* can be constructed in conjunction with the scale and ground. A variety of materials outside actuators can be tucked into *channels* through a knitted hole, without additional efforts for integration.

5.4.2 *Actuators*

KnitSkin enables locomotion through longitudinal extension of the sleeve. While the substrates can accommodate a wide range of materials, in this paper we build upon soft pneumatic actuators from past literature, due to its compliance and potential portability [207]. We specifically choose soft pneumatic actuators with pleated sheaths for their relatively high thrust force [246]. The pneumatic actuator consists of off-the-shelf materials: inner tubing (Super-Soft Rubber Tubing for Air and Water, McMaster), pleated sheath (Expandable Sleeving Gauze Polyester Fabric, McMaster) and custom 3D printed fittings. The pleated sheath can be made out of an expandable braided sleeve. The expandable braided sleeve is compressed axially, while it is maximally expanded radially, to form pleats. Then the sleeve undergoes heat treatment to secure the pleats. The resulting pleated mesh contains the radial expansion of the inner tubing, thus forcing the expansion to translate axially.

To expand the actuators, a compressor is used with a regulated output pressure of 42 psi. The compressor output is fed into the actuators through a 3-way pneumatic solenoid valve. The solenoid valve is fed with 12V pulses to achieve repeated expansion and contraction of the actuators. The solenoid valve is connected to a normally closed configuration. When the solenoid valve is supplied with 12V, the air flows from the compressor to the actuators and expands the actuators; and when the solenoid valve is supplied with 0V, the air in the actuators is exhausted through the exhaust port of the valve. The time period and the duty cycle of these 12V pulses is controlled using an Arduino controller. The 5V output of the Arduino is fed to a relay which switches the 12V supply to the actuator. A digital pressure gauge is also connected to monitor the pressure in the actuators.

5.5 KNIT SUBSTRATE PARAMETERS: TUNING FRICTIONAL ANISOTROPY FOR LOCOMOTION

One way to achieve frictional anisotrophy is to shape the surface with an array of angled *protuberances*. A protuberance is an obstacle on a surface, sometimes referred as bumps or hairs [66]. Filippov *et al.* [66] studied how protuberances can cause different frictions in different directions.

The scales in the KnitSkin can be seen as an array of protuberances. These protuberances have angles because the scale tips stack over the scales on the succeeding rows, as illustrated in Figure 21 (b).

Tuning granular details of the *scale* to examine their impact on the friction can be most effectively achieved by altering the parameters below. Here we lay out how the *scales* are formed on the knitting machine, and how the two primary determinants - scale *geometry* and *material* - influence the anisotropy of friction. While the two parameters complement each other, we focus on how geometrical parameters induce global effects across the fabric while material parameters dominate the behavior of an individual scale. All geometrical parameters presented below are based on a 5-stitch unit, except for the scale length parameter.

5.5.1 *Scale Geometry Parameters*

- *Scale length*: The *size* of a scale is determined by the number of needles skipped between two ends of a scale. When a yarn skips a needle, it runs across the back of the fabric instead of forming a knit loop. The free strand of the yarn forms a downward arch once the ground fabric is released from the needle bed. The *scale lengths* tested in this paper are 2, 5, and 11 stitches, shown in Figure 23 (a)(b)(c). Note 2-stitch is the smallest possible length in order for scales to curve.

- *Global pattern*: The *pattern* of scales influences the behavior of the substrate. In the knitting process, the scales are knitted row by row. This process controls how scales are stacked and which part of a scale is weighed down. When scales are stacked, the tendency to roll back diminishes as the adjacent scales are pressing down on them. For instance, in the zigzag pattern (Figure 23 (e)), each scale is stacked under the halves of two scales on the succeeding row, yielding the most balanced configuration. Scales in the diagonal pattern (Figure 23 (d)) leaves the right end of a scale uncompressed by adjacent scales. The wavy pattern results in a less controlled array from the side view (Figure 23 (f)). Note these three patterns have better rollback resistance compared with the column pattern used in Figure 23 (a-c), because the column pattern has the least overlaps among the scales.

- *Density*: The *density* is defined as the distance between two rows with scales. For example, a density of 1 row indicates the scales are knitted every other row. Figure 23 (g), (h), and (i) examine the densities of 1, 2, and 4 rows, respectively. Low density yields low anisotropic friction because it exposes more ground yarns, and the friction from the ground yarns is uniform across all directions.

5.5.2 *Scale Material Parameters*

While the geometrical parameters affect the global behavior of the substrate, the yarn material determines the characteristics of the scales.

Figure 24 demonstrates scales knitted with different types of materials. Considering the stiffness of the materials and their compatibility with knitting machines, we chose Nylon monofilament, 38 AWG copper wire and silver plated multi-filament (Lumina, 65% viscose, 35% metallized polyester, Silk City) for our experiments.

- *Material roughness*: The surface and cross-section of a material influence the overall roughness of the substrate, which in turn impacts the friction. Single filament materials such as nylon monofilaments and metal wires exhibit smoother surfaces; they have a solid cross-section, often in the shape of a clean circle. On the contrary, multi-material yarns such as silver plated multi-filament consist of a core yarn and a wrapper, displaying a non-uniform cross-section. The bristly surface of multi-material yarns, which are akin to the metal-plated ones, can also be attributed to the incoherent yarn composition. Likewise, staple yarns or spun yarns which are composed of fibers cut to short lengths tend to have a "fluffy" surface texture. However those staple yarns are deemed unsuited for knitting scales as they tend to lack stiffness.

- *Material rigidity*: The *curvature* of scales is closely tied to the capability of the material to store tension during and after the knitting process. We observe that the scale curvature is determined by the two main facets: material *stiffness* and *elasticity*. For instance, while

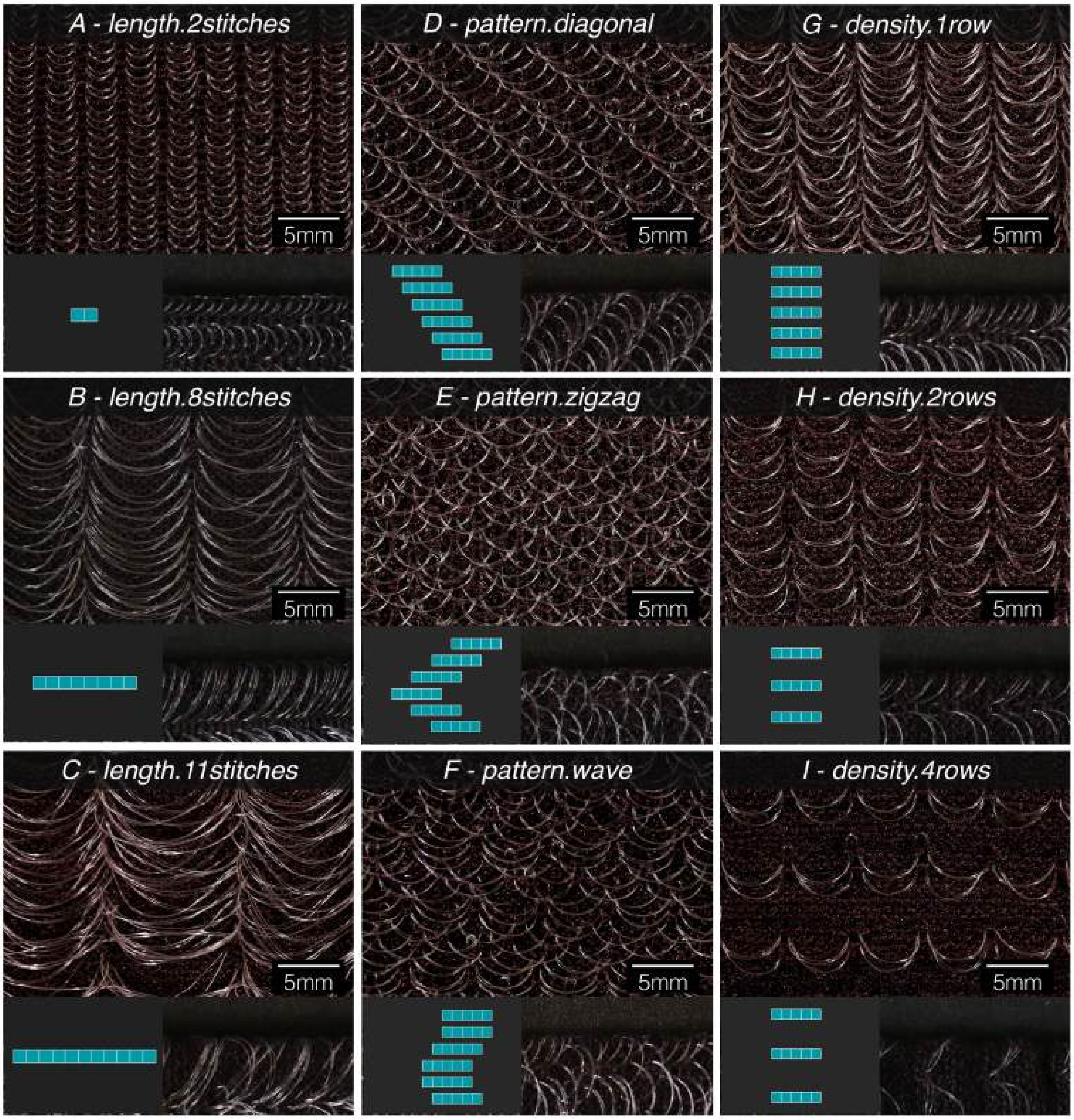

Figure 23: Geometry parameters of scales. The notations on the bottom left corner of the cells denote the numbers and configurations of stitches to form *scales*. The dark background of the notation represents *ground layer*. Presented in each cell are resulting substrates from top and side views.

the stiffness of copper wire produces some degree of curvature, the lack of elasticity makes it prone to getting bent permanently without rebound (Figure 24 (b)). Yarns with little stiffness, as well as little elasticity, such as Puma (80% viscose, 20% Elite, Silk City) do not get stressed under knitting, thus straightening out post knit (Figure 22 (b)). Similarly, materials with excessive stiffness (e.g., copper wires thicker than 34 AWG) cannot withstand the stress and are likely to break during knitting.

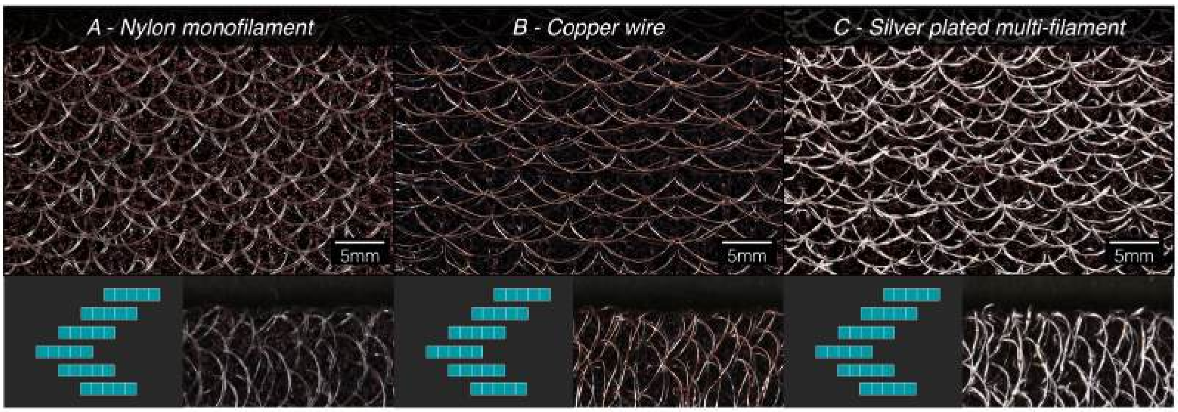

Figure 24: Material parameters of scales. With the same stitch length and pattern, varying materials affects the properties of an individual scale, which in turn affects anisotropic friction.

5.5.3 *Resulting Anisotropic Characteristics*

The head-to-tail direction of the scales determines the anisotropy of the substrate; it is expected to experience the most friction with the movement travelling towards the tail, and the least towards the opposite direction. Since scales point to the tail (Figure 21 (b)), we can anticipate it will take the least amount of force to move KnitSkin forward (towards the head direction) and the most force to move it backwards (towards the tail). To quantify the anisotropy, we define the *force ratio* as the force to move KnitSkin forward, over the force to move it backward. The ratio is anticipated to be below 1, and the smaller the ratio, the easier for KnitSkin to move towards one specific direction (i.e., forward.)

To measure the force needed to move the KnitSkin towards these two representative directions on a cylindrical surface, we connect the initial load on one of both ends, and increment loads until displacement is observed. We first test the *material* parameters (nylon monofila-

Table 1: The force ratios of pulling KnitSkin forward over pulling backward under different materials (demonstrated in Figure 24.) A smaller ratio indicates that it is easier to move KnitSkin *forward* with the setup.

Material Parameters	Ratio	Material Parameters	Ratio	Material Parameters	Ratio
A - Nylon monofilament	**0.873**	B - 38 AWG copper wire	0.881	C - Silver plated multi-filament	0.927

Table 2: The force ratios of pulling KnitSkin forward over pulling backward under different geometry parameters (demonstrated in Figure 23.) A smaller ratio indicates that it is easier to move KnitSkin *forward* with the setup.

Geometry Parameters	Ratio	Geometry Parameters	Ratio	Geometry Parameters	Ratio
A - length.2stiches	0.917	D - pattern.diagonal	0.911	G - density.1row	0.994
B - length.8stiches	0.889	E - pattern.zigzag	0.768	H - density.2rows	0.918
C - length.11stiches	0.693	**F - pattern.wave**	**0.692**	I - density.4rows	0.997

ment, 38 AWG copper wire, and silver plated multi-filament (Figure 24)) then proceed with the *geometry* parameters (Figure 23) to find out the most optimal setup. Each setting is tested 5 times to account for variability. Attributes of the cylinder and other experimental set up remain the same across the entire experiment for consistency.

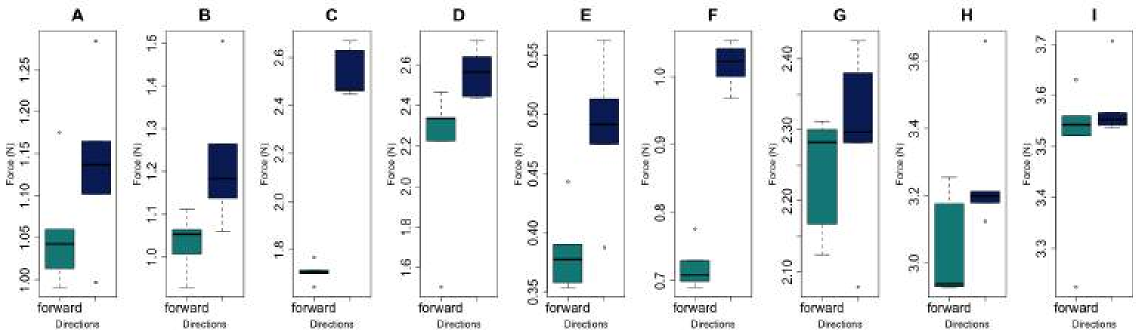

Figure 25: The distribution of force values under geometry parameters. Monofilament scales varied across different scale lengths, global patterns and density. While the medians between the forward and backward directions across *density* show trivial gaps, the medians of all variations indicate greater force required for the backward displacement

Our data shows that for backward force, namely when the slope of the scales interlocks with the surface, greater force was required regardless of materials (Table 1). Among the materials the nylon monofilament recorded the greatest gap between the head (forward) and tail (backward) directions. 13.6% less force was needed when the slope of scales was positioned forward. While the 38 AWG copper wire produced similar less force of 11.8%, the silver plated multi-filaments recorded the least amount of force gap of 7.2%. Following the result, we chose the monofilament to test the *geometry* parameters. Of eight variations, the one that yielded the greatest force gap was *f* (Figure 23). All eight variations indicated greater force for backward displacement. Nonetheless, we noticed that the *density* variations overall informed of an insignificant gap less than 10%, which could be a result from a greater exposure of the ground yarn than *pattern* and *scale length*.

5.6 LOCOMOTION EVALUATION

In our preliminary characterization we investigated parameters of *scales* and their influence on frictional anisotropy. The objective of this study is to understand the propulsion ability of KnitSkin by deploying it on actual cylindrical terrains. In order for KnitSkin to serve inter-scale uses it is critical to leverage its design and realize locomotion on a wide subset of cylindrical surfaces. In this evaluation, we focus on how the individual variables below affect the traversal distance. The interaction between the variables is not the focus of this investigation.

5.6.1 *Surface Materials*

The traversal distance is the result of a variety of interfacial properties involving the underlying surface materials and their roughness [66]. In the study we aim to inspect a wide range of materials through which we envision use cases of KnitSkin across various applicable scales.
Procedure and Apparatus. During the test, we used a knitted substrate configured with the knit pattern f from scale parameters (Table 2) and nylon monofilament material, following the results from the anisotropy characterization (Table 1). Three pneumatic actuators were spaced evenly and integrated in the sleeve, with the pressure at 42 psi. We use the distance that the interface travels in 10 inflation-then-deflation cycles as our evaluation metric. Each cycle involves a 3-second inflation and a 1-second deflation. We repeat this for 10 rounds for each parameter. The slope of the surface was set at 0 degrees, with a diameter of 2 inches.

The list of surface materials evaluated includes: extruded polyvinyl chloride (PVC), reinforced vinyl, steel, polyurethane laminate (PUL, 75% polyester, 25% polyurethane), silicone rubber, and neoprene. The selected materials cover a wide range of cylindrical surfaces that KnitSkin can climb on: PVC, reinforced vinyl, and steel represent materials widely used in industrial applications; PUL, silicone rubber, and neoprene have similar properties to human skin [61].

Prior to the evaluation, we use a profilometer (10x, Keyence VK-X260 Laser-Scanning Profilometer) to scan the surface and to measure the roughness (i.e., the characteristics of peaks and valleys on the surface) for each material. The scanned images and the 2-point profiles (i.e., the surface elevation and depression along a straight line) are presented in (Figure 26). As conduits which are extruded during fabrication, PVC and reinforced vinyl tubes present horizontal textures. While both PUL and steel show recognizable depressions, the ones on PUL span across larger area. Neoprene and silicone rubber indicates relatively shallow and small bumps.

We use *developed inter-facial area ratio* (denoted as *Sdr*) to quantify surface roughness [174]. The ratio is defined as the of the additional surface area contributed by the texture normalized by the area of interest. Thus, a rough material results in a larger ratio due to the additional area contributed by peaks and valleys.

Results. The results (Figure 26) show that the KnitSkin travelled the furthest distance on the PVC cylinder. While locomotion on the PUL started off by outrunning that on PVC, it started to slow down after 3 cycles.

5.6.2 *Number of Actuators*

Procedure and Apparatus. The knitted substrate maintained the pattern *f* from scale parameters (Table 2) and nylon monofilament material (Table 1). The PVC cylinder with a diameter of 2 inches was placed parallel to the ground. The number of actuators is the only varying factor in this test. The possible configurations are two, three and four actuators. The actuators were spaced evenly apart across the circumference of the substrate. The pressure is set at 42 psi, with a sequence of inflation-then-deflation cycles.

Results.

Our results suggested KnitSkin travelled further when there were more actuators. The three- and four-actuator setup travelled 1.1x and 2.4x compared with the two-actuator case. Through the visual inspection during the test, we found the four-actuator setup performed much better than the other two because more actuators help transfer their local extension globally. On the contrary, in the two-actuator case, the substrate between the actuators remained static, and the

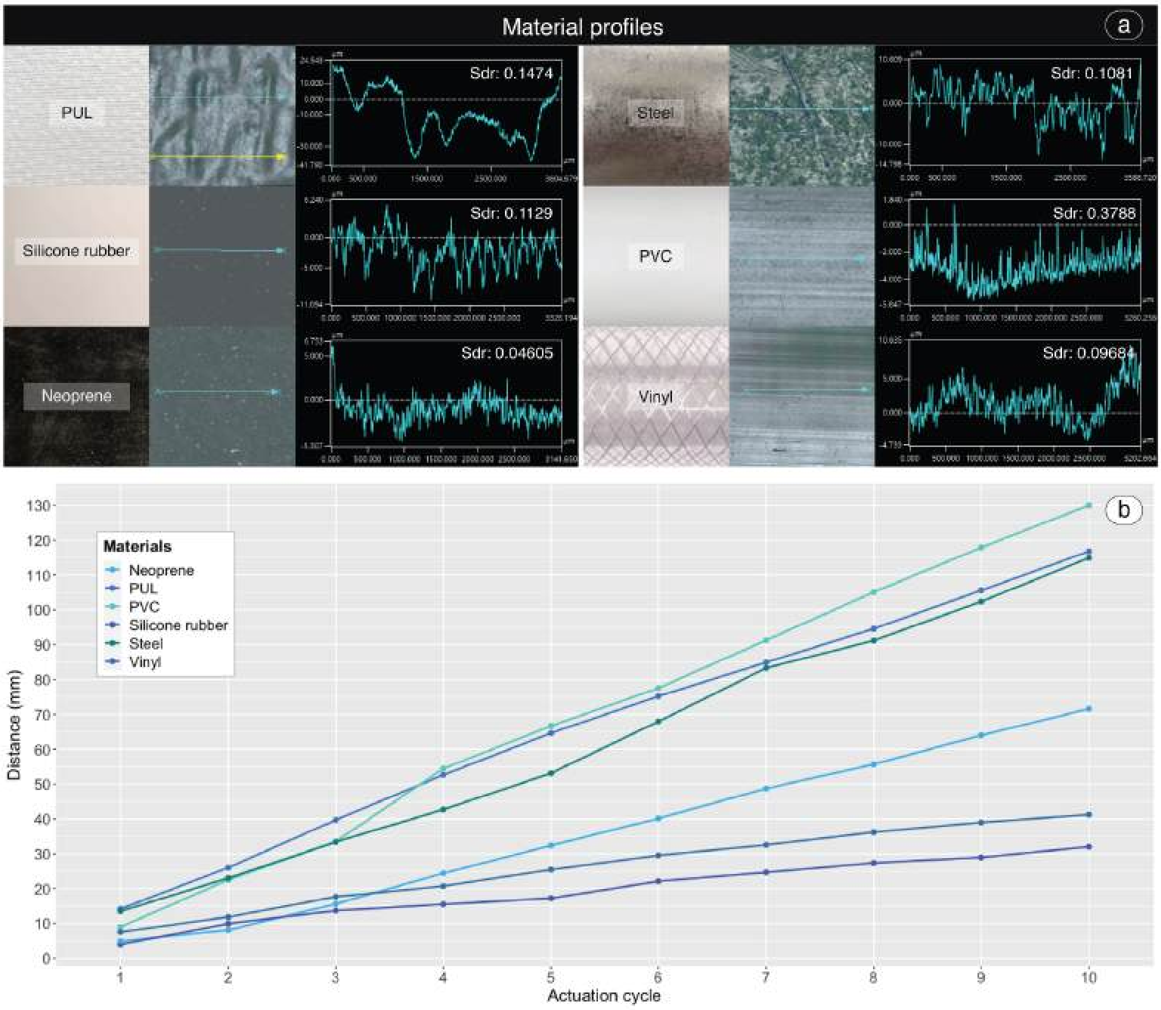

Figure 26: The effect of surface material on travel distance. (a) Demonstrates raw images of surface materials, images of the materials scanned with a profilometer, and 2-points profile from left to right of the arrows. We present values of *Sdr* as a roughness parameter. (b) Presents locomotion distances in millimeter by actuation cycles.

actuators were more prone to bending. This indicates that if extension was disproportionately concentrated to one or two of the actuators, the local extension would not transfer throughout the substrate.

5.6.3 *Slope of Terrain*

Procedure and Apparatus. The knitted substrate maintained the pattern *f* from scale parameters (Table 2) and nylon monofilament material (Table 1). Following the results from the previous test, four pneumatic actuators were spaced evenly and integrated in the sleeve, with pressure of 42 psi. We used a PVC surface, varying the slope from 20, 30 to 40 degrees.

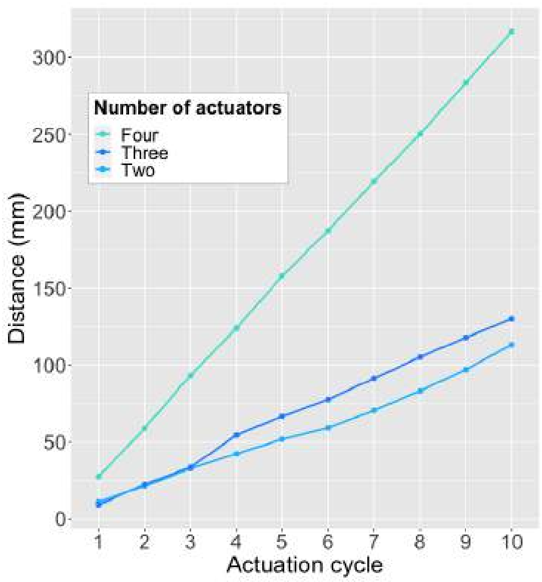

Figure 27: The effect of the actuator number on travel distance.

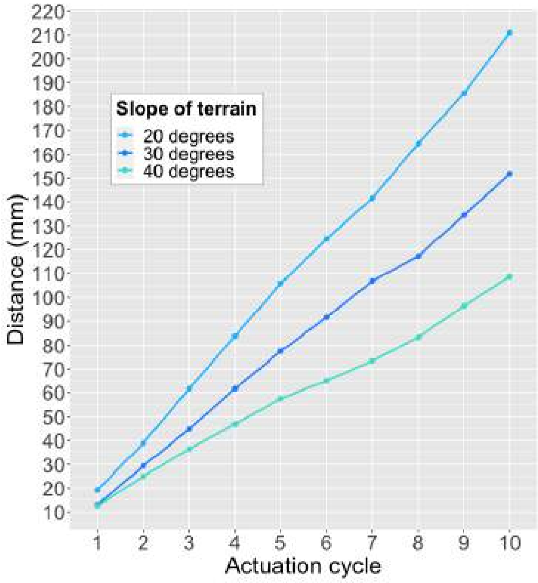

Figure 28: The effect of the slope of terrain on travel distance.

Results. We observed a decrease in the traversal distance when the slope became steeper (Figure 27). Compared with the 20-degree slope, we observed a 30% and 50% drop at 30- and 40-degree cases, respectively. The performance degraded considerably when the terrain is tilted beyond 40 degrees.

5.6.4 *Curvature of Terrain*

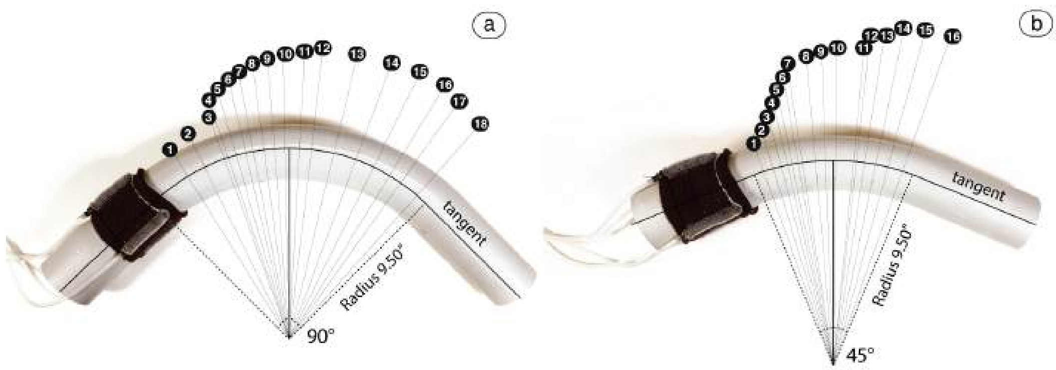

Figure 29: (a), (b) Locomotion on 90 and 45 degrees curved terrain. The numbers denote the progression of locomotion cycles. The intersection between the central arc and the corresponding lines is where the substrate concluded a cycle.

Procedure and Apparatus. To evaluate if the substrate can propel on a curved cylindrical terrain, we prepared two PVC pipes (i.e., curved cylinders) bent by 45 and 90 degrees, with the same radius of 9.5 inches. The pipes were placed flat on the ground. We placed the substrate at the starting position before the curvature (Figure 29), and tested if the substrate could crawl and pass the peak. Similar to prior setups, the knitted substrate used pattern *f* from Table 2 and nylon monofilament material (Table 1). Four pneumatic actuators were spaced evenly and integrated in the sleeve. In this test we did not implement 10 cycles. Instead, we sought to observe how many cycles would be repeated for the substrate to pass the curve and enter the tangent on the other side.

Results. The result of the test indicated that the substrate was able to propel through the curves. The distance progressed in each cycle dwindled when passing the peak curves, but the substrate picked up pace after the curve was passed. It took 18 cycles for the substrate to pass the 90 degrees curve whereas 16 cycles were implemented to pass the 45 degrees curve. The locomotion on the 90 degrees curve tended to slow down during the peak curve, as demonstrated from 3rd to 10th cycle (Figure 29 (a)). On the other hand locomotion progressed relatively evenly on the 45 degrees curve, as the even distances between cycles demonstrated (Figure 29 (b)). Our visual inspection notified us that when the substrate was passing through the most curved region of the 90 degrees terrain, the actuator on the inner most arc extended off the cylinder axis; it did not conform to the curvature during actuation but extended along the chord. This created an area where few scales seemed to be in contact with the terrain, which could have driven the sluggish locomotion on the 90 degrees terrain.

5.7 APPLICATIONS

We demonstrate applications of KnitSkin on various surfaces, from the wearable scale, to the industrial and environmental scales. We build on our insights from the evaluation section for selecting our application contexts.

5.7.1 *Wearable and Relocatable Interface*

In evaluating a variety of surface materials, we learned that the KnitSkin substrate can crawl on synthetic materials which share the properties of human skin, such as PUL, silicone rubber and neoprene [61]. Given its soft and knitted form, KnitSkin resembles clothing, making it an

Figure 30: KnitSkin, as a wearable interface carrying a microphone, relocates to a suitable location on the arm when answering a phone call.

appropriate form factor for on-body locomotion. In addition to the form factor, the channels' ability to accommodate a wide range of actuators means it can be altered to create a pocket for input sensors and output feedback modules. Taking advantage of such attributes, we envision a relocatable wearable interface that can change its location for voice input (Figure 30). When the interface receives an incoming call while both of a user's hands are busy, the interface crawls down to the lower arm for easier voice input. In this application we modify channels to enfold an accelerometer for detecting the motion of both hands which in turn triggers locomotion. We used an open-soure, miniaturized portable compressor, FlowIO [207], to pressurize the actuators for a wearable context. The FlowIO device is connected directly to the actuators and is programmed to periodically inflate them to a predefined pressure, followed by subsequent exhaustion of the air to produce the desired locomotion. While we demonstrate this in the application of an everyday interaction, we envision it can also be used widely for health and rehabilitation applications. Owing to the channels that can be designed to enfold a wide range of materials outside the list proposed in this paper, materials to serve other function such as shape memory alloy (SMA) can be integrated. With the freedom in channel design, one can configure lateral channels in addition to the longitudinal ones to enclose SMA along the circumference of arm. The interface would climb up and down the arm to convey compression on varying locations.

Figure 31: The KnitSkin ground layer can be knitted with a wide range of materials, including water soluble PVA yarn. When KnitSkin travels along a pipe and becomes exposed to a leakage point, the PVA yarn dissolves, forming a protective layer on the point of leakage.

5.7.2 *Industrial Applications*

The programmability of the *ground layer* and *scales* affords the use of diverse and unconventional materials for knitting. By knitting in a strand of water soluble polyvinyl alcohol (PVA) thread to *ground layer*, we can transform the substrate into an interface that passively reacts to environmental moisture. We present an application of a pipe-leakage monitoring and protection sleeve. The interface can travel along the length of a pipe and reach inaccessible regions, and when it gets exposed to water leakage, the PVA thread dissolves and solidifies the entire substrate to stop the leak. By nature of PVA thread, the dissolution induces considerable shrinkage of the substrate, resulting in a tight grip of the interface around the leak location. As the interface dries it remains solid. The resulting interface could serve as a temporary fix for a water leak without requiring external sensing systems (Figure 31).

5.7.3 *Agricultural Applications*

We highlight how non-smooth surfaces aid locomotion for KnitSkin. Complying with Filippov *et al.* [66] and the earlier test results from Figure 26, we apply KnitSkin to surfaces with more conspicuous texture. Bark-clad tree branches offer not only an ideal condition for locomotion but also a unique application space. Crawling up vertical trunks and angled branches, KnitSkin can serve as a soft, relocatable tree guard. KnitSkin could offer a simplistic solution to common issues with existing plastic wraps, which leave a nasty abrasion and can result

Figure 32: By modifying channels into pockets for a portable pesticide dispenser, KnitSkin can further work as an agricultural robot.

in bark disease due to the excessive moisture captured inside. The porous structure of knits lets air flow freely through the substrate, while relocating itself with least damage to the tree (Figure 32). Alternatively, the *ground layer* could be knitted with insect repellent yarns [283] to protect young trees from insect pests which can be harmful for the tree. If equipped with a portable pesticide spray, KnitSkin could also serve as a minimally intrusive pesticide dispenser that does not spread unneeded chemicals to other trees.

5.8 DISCUSSION AND FUTURE WORK

We demonstrated that KnitSkin's effective locomotion strategy was compatible with various terrain characteristics ranging from material, slope angle, and curvature. However, quantifying detailed physical characteristics beyond what's studied in the paper is warranted for encompassing more diverse environments. This includes understanding the impact of tapered or helical terrain on locomotion, bumps and depressions on movement robustness, and gravitational forces on varying terrain slopes and orientation. While KnitSkin offers many methods to configure custom channels and scales to meet diverse terrain needs, maintaining consistent normal force against a surface remains a challenge. To this end, it will be beneficial to investigate the interaction between the factors which impact locomotion, as listed in Section

5: Locomotion Evaluation. Additionally, for KnitSkin to evolve as an on-body interface, an untethered prototype using miniaturized pumps and remote communication should be integrated. Future work will explore creating an untethered compression system in which we equip each actuator with a portable pump. Soft actuators fabricated with alternative means, for instance, fiber-reinforced actuators [256], could help KnitSkin achieve a slimmer form factor.

5.9 CONCLUSION

We presented KnitSkin, a *soft* approach for generating locomotion on cylindrical surfaces. We introduced the fabrication of a knitted scaled skin, which consists of the *ground layer*, the *scales* which contribute to surface friction, and the *channels* for integrating actuators for propulsion. We defined the *scales* as the primary contributor to the anisotropic friction of the substrate. We characterized geometric and material parameters of the *scales* for realizing movement. In evaluating locomotion, our experiments revealed the effect of surface materials, the number of actuators, and terrain slope on traveled distance. We also qualitatively inspected locomotion on a curved terrain. Drawing insights from the evaluation, we proposed applications across different scales: *wearable*, *industrial*, and *agricultural*. Taking inspiration from nature, KnitSkin exemplifies the versatility of machine knitting in creating a unique bio-inspired substrate that enables underexplored locomotion technologies on cylindrical terrains.

5.10 positioning knitskin within the design space

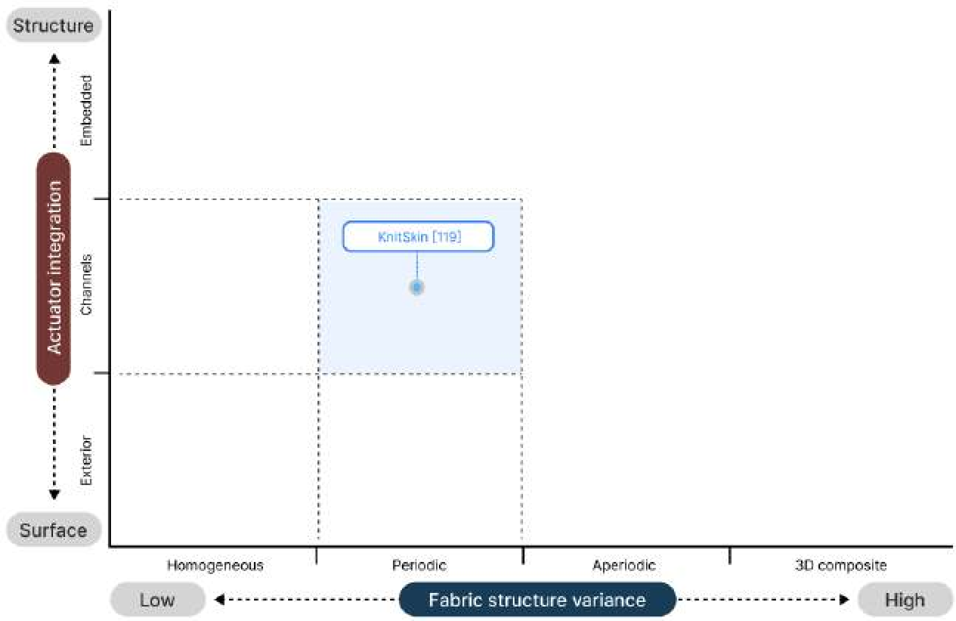

Figure 33: Situating KnitSkin in the design space.

KnitSkin is a device that utilizes unique anisotropy in friction, mimicking the movement of snakes in nature. By incorporating *periodic* constituent structures, KnitSkin introduces surface roughness, which, in tandem with the linear motion of the actuator, creates directional movement. The integration of powerful soft pneumatic actuators is made possible through propped-up fabric *channels*, without compromising the fabric's elasticity and flexibility (Figure 33). This locomotion is achieved through an interplay of material properties and mechanical design, ensuring that the device can move effectively while maintaining a snug and comfortable fit against the skin.

6

ROBOTIC TEXTILES FOR PERISTALTIC COMPRESSION

Each of the preceding chapters leading to this chapter has discussed a single project dedicated to a particular form factor to serve chapter-specific functionality in detail, situating it within the design space. In these chapters, the devices were fabricated by technicians and HCI researchers with years of experience in digital knitting and extensive knowledge of actuators and material properties.

In this chapter, I illustrate the cumulative process, contributing not only to the fabrication of a device dedicated to a specific application but also addressing the limitations of the current fabrication process that restrict access for a broader group of designers. This chapter comprises two projects, with the first phase dedicated to the fabrication of a robotic textile device that generates active compression for a group of edema patients (Section 6.1). In this initial project, I collaborated with medical professionals at Weill Cornell Medicine to employ robotic textiles as therapeutic wearable devices for patients with edematous hands requiring frequent and consistent physical therapy. The clinicians and knitting technicians (including myself) achieved functional and successful devices through the co-design process. However, it became evident that the existing programming knitting methods were ineffective for clinicians who wished to adapt and customize the design in real time while working with patients. The pixel-based programming proved to be excessively time-consuming to learn, and the likelihood of clinical facilities owning a knitting machine was minimal, further restricting access to this fabrication method.

In response to these challenges, a second phase was developed (Section 6.12). This new iteration features an intuitive design tool specifically created to enable clinicians to easily modify and customize the device as needed. This tool aims to bridge the gap between the technical complexities of digital knitting and the practical needs of clinical applications, thereby empowering clinicians to utilize robotic textiles in a more accessible and efficient manner. In this phase, I present case studies demonstrating how clinicians employed the design tool to fabricate and customize devices specific to individual patients. These case studies highlight the differences and takeaways between the design tool-aided fabrication process and that of traditional knitting technicians. The analysis also reveals the factors and priorities that influenced the clinician-led design process.

6.1 Phase 1: KnitDema—Robotic Textile as Personalized Edema Mobilization Device

This chapter is based on the published work on KnitDema, a device specifically engineered to fit a person's hand and apply pressure in sequence to treat hand edema. KnitDema emerges from a need for personalized rehabilitation devices for edema that can adapt to more granular parts of the body, such as the hand. Traditionally, treatments for conditions like edema have relied on bulky pneumatic systems designed for larger body parts, like limbs, which do not offer the same level of precision or comfort.

What sets KnitDema apart in the design space is its push towards a high degree of personalization. The device is uniquely tailored to both the anatomical area it serves and the individual characteristics of the user. Such a device would not be suitable for any other part of the body or any other user, highlighting its bespoke nature. This high customizability was made possible by the fine tunability of the knit structure.

In this context, KnitDema is situated within the *aperiodic* scale of the *fabric substrate* parameter, ensuring that the device conforms precisely to the specific user's body shape through shaping techniques. These involve the active manipulation of stitches both across and along the knitting bed, allowing for significant alterations in the device's shape while providing the necessary elasticity. This geometry is crucial for accommodating swollen hand shapes.

By leveraging these advanced knitting techniques, and seamlessly integrating nitinol actuators into fabric *channels*, KnitDema demonstrates how bespoke, body-conforming wearable devices can be designed and fabricated to meet individual needs, showcasing the potential of digital knitting in creating highly specialized robotic textiles.

The development of the KnitDema device was a collaborative effort with Joan Stilling and Michael O'Dell from Weill Cornell Medicine, and Cindy Hsin-Liu Kao advised on this. In this chapter, I will use "we" to reflect the joint effort in creating the device. The content presented here is derived from the paper of which I'm the primary author, "KnitDema: Robotic Textile as Personalized Edema Mobilization Device," published at the ACM CHI 2023 conference [120].

6.2 INTRODUCTION

The COVID-19 pandemic and at-home social isolation have highlighted the need for personalized healthcare strategies that can empower people to manage non-life-threatening medical conditions without frequent hospital visits. Prolonged hand edema can affect the range of motion, active movement, and everyday human functional ability. For example, reports indicate that 73% of persons post-stroke have experienced hand swelling and that it severely impacted the quality of life [25].

Hand edema is caused by an abnormal buildup of interstitial fluid and can occur throughout the hand [75]. Current edema treatment or management is provided in clinical settings, often requiring manual massage by physical or occupational therapists (PT/OT) for mobilizing edematous fluid [153, 154]. While manual massage can be customized to individual patient needs, the cost of highly trained personnel providing labor-intensive treatment has deterred a scalable and widely applicable strategy.

Other common treatments, such as intermittent pneumatic compression (IPC) devices, are extremely bulky and not customizable to individual anthropometry. Thus, there is a lack of *cost-effective*, *customizable*, and *portable* edema treatment strategies for use outside a hospital or clinic setting.

To close this gap, we present KnitDema, a *robotic textile* system that provides sequential compression across finger phalanges for mobilizing hand edema. Robotic textile is an emerging form of fabric-based soft robots that enable "sensing, actuation, and stiffness control" in "a single conformable fabric substrate" [28, 29], creating a new platform of robots to offer compliant structures compatible with wearables.

Robotic textiles can be especially suitable to the needs of hand edema treatment in terms of (1) individual customization, (2) accessibility, and (3) comfort.

Diverse etiologies and presentations of edema in individuals are among the main challenges that make hand edema difficult to treat; individuals must comply with different treatment timelines and regimes. The diverse hand shapes and swelling presentations are compounding this problem, making standardized treatment difficult. KnitDema caters to individual medical needs and anthropometry of the hand by offering programmable compression parameters and leveraging machine knitting which can fabricate made-to-measure devices. Highlighting accessibility, KnitDema can be programmed to deliver a sequence of automated actuation from the comfort of the patient's home, alleviating the need for costly and frequent therapy visits to clinics. Further, unlike IPC, robotic textiles are comparably inexpensive and easy to fabricate with standard textile machinery. Finally, KnitDema affords superior comfort because it is breathable and comfortable to wear. Compliant fabric and small-scale actuators allow the device to reach granular parts of the hand without fatiguing the hand in long-term use. The textile-based device does not encumber patients with bulky bladders, compressors, or oversized form factors.

To understand patient's needs from multiple perspectives, we adopt a co-design process [51, 96, 97] in which a collaborative team of human-computer interaction (HCI) researchers, rehabilitation physicians, and hand therapists iteratively developed the device and study protocol over 1.5 years. Integrating slim shape memory alloy actuators in machine-knitted textile structures, KnitDema affords sequential compression by actuating low-profile substrate attached to a portable printed circuit board (PCB) controller. We identify compression parameters for the developed system and characterize them in-vitro utilizing a mock fluid displacement system. This culminates in a human subject case study with persons with hand edema to understand the feasibility of the KnitDema system. Throughout this longitudinal co-design process, the researchers and physicians gained insight into managing and treating edema from an interdisciplinary perspective. We further reflect on this process to benefit co-design processes in other realms of health technology. We make the following contributions:

- We present KnitDema, a robotic textile system that can provide sequential compression from distal to proximal finger phalanges for mobilizing hand edema. Fabricated with customized machine-knitted substrates, the device can envelop granular body locations such as fingers, catering to individual hand shapes and edema presentations. In addition, the device affords adjustable compression levels through pulse width modulation (PWM) of enclosed shape memory alloy (SMA) actuators.
- We simulate the fluid displacement of the device through a mock system emulating the shunting of interstitial fluid to characterize the impact of (1) the number of SMA bands, (2) the duration of compression, and (3) the intervals between SMA bands and sequence on the fluid drainage.
- Using the developed system and identified parameters, we conduct a case study with 5 persons with hand edema to understand the system's feasibility.

6.3 RELATED WORK

6.3.1 *Treatment Regimens of Edema*

Various disorders can cause edema to manifest with different presentations on the body. While treatments of edema can vary by individual, "mobilization of excess fluid" is the primary goal in treating edema. Literature identifies common treatment regimens as active compression and manual edema mobilization (MEM) [153, 154]. Active compression involves electrical components that exert forces on the body to move interstitial fluid through the lymphatic system. Intermittent pneumatic compression (IPC) is one of the most widely applied devices of this sort [74], in which pneumatic chambers wrap around the limb, compressing it as the chambers inflate. To mobilize fluid, subsets of IPC come with capabilities to inflate chambers sequentially [183] and with force gradients [46]. IPC devices have demonstrated effectiveness for a wide range of diagnoses from breast carcinoma [226] and lymphedema [59, 275] to deep-vein thrombosis [5]. Nonetheless, the sheer size and bulkiness of IPC devices make them difficult to treat granular parts of the body, such as fingers or hands. Moreover, the uniform form factors of IPC prevent treatment from catering to individual body shapes.

Another prominent method to reduce edema is manual edema mobilization (MEM) [24, 188], or retrograde massage therapy, which involves therapists applying light traction on the skin along lymphatic pathways. MEM allows more delicate management and accommodates patients' body shapes as therapists rub the convexes and concaves of the body. MEM has also proved efficacy across lymphedema [102], and sub-acute hand edema [154]. However, MEM therapy can be difficult to perform without trained therapists.

Outside common treatment regimens, there are other ways to reduce swelling in the extremities. Fluidotherapy [88] is one, which involves fine solid particles flying in a hot dry whirlpool to stimulate the body. Analogous to IPC, fluidotherapy requires tethered devices that take up space and are not readily available outside clinics. There are also compression garments, and Kinesiotaping [20, 100], or taping, for passive compression. While passive compression can be more accessible and readily available, literature renders it as more of a maintenance regimen than active management to reduce swelling due to decreased efficiency and prolonged intervention time [100].

KnitDema contributes the first step towards a portable and compliant active treatment device. While the device retains the wearability of passive compression garments, it adds active compression, which can also be prescribed to individual patient needs. Further, KnitDema allows for accessible treatment for patients with impaired physical mobility or who have difficulty accessing clinics to receive therapy ultimately wherever convenient.

6.3.2 *Robotic Textile in Medical Applications*

As defined in the literature, robotic textiles enable sensing, actuation, or stiffness control embedded in a single compliant substrate [29]. In particular, robotic textile with actuation capability brings attention to the potential of shape-changing textiles for versatile applications. Actuators with small footprints or "functional fibers" [28, 29] give motion to robotic textiles for load-bearing [273], haptics [224], thermoregulation [243, 263], hand rehabilitation [31, 62], gait assistance [230], or therapy [239]. As an emerging form of planar and soft robots, robotic textiles typically serve as an embodied contraption worn by the wearer. The textile-based contraption enhances [200] and rehabilitates [217] the wearer's muscle capacity from proximity to the skin. While there have been approaches to integrate actuators into woven fabrics [126, 224], manipulation of woven textiles remains limited due to the inherently inextensible nature of weaves. Knit stands out as its versatile loop-by-loop structure enables multiple degrees of freedom in motion when coupled with desirable actuation [139] and anisotropic manipulation when used in conjunction with other strain-limiting layers [166].

Robotic knit is an attractive medium to be used in conjunction with suitable actuators, especially for rehabilitation applications. In the past, many approaches have focused on aiding the musculoskeletal movement of muscles through pneumatic actuators or bladders. In those applications, knit selectively allows strain of the pneumatic actuators to help with grasping [62, 264, 280], locomotion [230], abduction or adduction [170, 280]. To date, there has been little emphasis on reducing the scale of this rehabilitation equipment while maintaining adequate force generation. However, growing interest in rehabilitation devices has started to move the field toward this sophisticated manipulation of muscle [196] enabled by high DOF or small-scale actuators [116].

Containing actuators within a conformable substrate, KnitDema's goal aligns with this transition; the project aims to treat swollen fingers, which may encumber patients if using bulky actuators from the above conventional contexts. While the fiber-scale actuators [116] do reduce device size, the need for a portable pump and tube does not align with KnitDema's objective to be a small-footprint device. We build on and further extend the fabrication introduced in [118], in which shape memory alloys were integrated inside a knit substrate to render tactile feedback, extending it for medical application.

6.3.3 *Co-Designing with Clinicians*

As with other diseases, there are no two identical manifestations of edematous hands. It is thus vital to understand patient needs through clinicians and therapists to fabricate treatment devices that can accommodate the attributes of individuals. In interdisciplinary studies in

HCI, co-designing methods [51] in the past have helped researchers channel domain-specific knowledge and insights to projects, yielding fruitful results.

In the past, researchers and therapists have co-designed assistive technologies [96, 97] to enable digital fabrication and methods for rapid prototyping for patients. Through observing and interviewing clinicians, researchers gained insights and worked collaboratively with therapists to deliver assistive technologies that meet patients' needs. In a similar clinical context, researchers have utilized "design cards" to help therapists conceptualize telehealth media that could potentially be deployed in their practice [101]. After holding onto the cards for a week, therapists rejoined researchers again and shared perspectives on how the telehealth media can be considered invasive. Researchers have also conducted long-term ethnographic studies with patients in an attempt to enhance current implanted cardiac devices (ICD) [12]. Researchers provided ICD patients with a web platform and an app in which patients would voice-record their clinical and mundane experiences with their ICDs. Accumulated feedback helped researchers gather information on the current cardiac devices and brainstorm potential improvements.

The above examples of co-design research demonstrated success in closing the gap between clinical domains and HCI research. In this work, we extend the co-design process specifically to the fields of rehabilitation and robotic textile development. Over 1.5 years, our team of HCI researchers, rehabilitation physicians, and PT/OTs iterate on the full scope of the project, which runs the gamut from preliminary experiments, hardware development, and form factor design, to implementation in the case study.

6.4 OUR CO-DESIGN WORKFLOW

The co-design process in this research covered the end-to-end workflow from early brainstorming of the device to the human subject user study in which persons with hand edema experienced the device. We adopted co-design [51, 96, 97], and research through design [281] to inform and complement our workflow.

Co-designing process spanned from building the *device* to developing the *device-patient experience* during the user study. The process involved a collaborative team of HCI researchers,

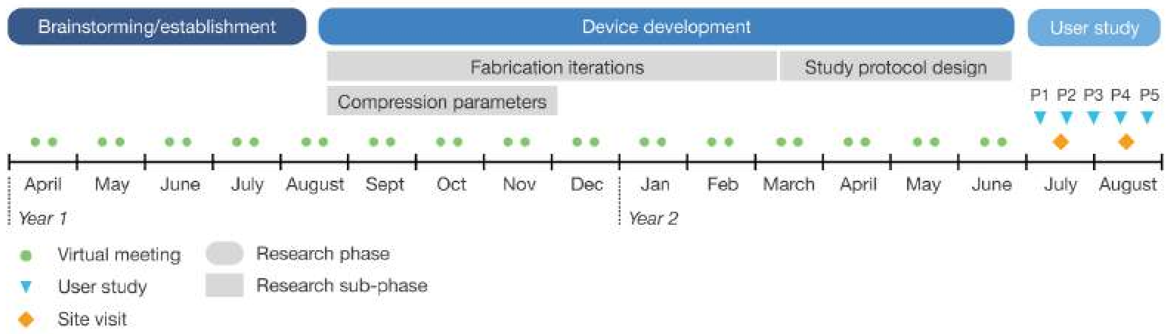

Figure 34: Timeline of co-design workflow

rehabilitation physicians, and physical and occupational therapists (PT/OTs) from Cornell University (CU), Weill Cornell Medicine (WCM), and Cayuga Medical Center (CMC), respectively.

The HCI researchers spearheaded the development of the device, characterized compression parameters, and wrote an IRB-approved protocol for the user study, with guidance from rehabilitation physicians. Therapists at CMC contributed practical knowledge on the mechanics of manual edema mobilization, current management of edema from a patient's home, and the logistics of edema therapy in general, and supported the recruitment of patients for the study.

Exchange of Expertise. This early phase of the co-design process was in part informed by [96, 97, 212], in which the parties that *produce* the device and patient-device experience come together to share expertise and domain-specific knowledge to establish collective research goals while keeping the *recipients* (i.e., patients) of the product in mind. HCI researchers held bi-weekly remote meetings with rehabilitation physicians starting from April of Year 1, as CU and WCM are situated in different cities. HCI researchers began by introducing the concept of robotic textiles, actuation mechanisms, and control, along with the mechanical properties of shape memory alloys, constraints in machine knitting, and early conceptualization and schematics of the device. Physicians shared the causes and clinical presentations of edema, current treatments, and the downsides and upsides of those treatments. While the bridge between the two teams moved the development of the device along, HCI researchers were keen to learn about the actual procedure of therapy in practice and the role of therapists in engaging with patients. The researchers reached out to therapists at a local rehabilitation clinic, CMC, which served as the primary recruiting site for the user study, to understand firsthand what engaging with prospective participants entails. HCI researchers and therapists at CMC convened on a regular basis before and during the user study to conceptualize desirable patient-device experiences. Through the established link between the two parties, researchers learned the average duration and program of therapy, how to "work" the swollen hand to massage tissues along the nodal pathway as the excess fluid drains out from the hand, and how other external factors such as temperature and humidity affect patients.

Cross-Disciplinary Iterations. These concurrent discussions across different institutions helped expand the scope of the project's co-design beyond HCI, and to include therapists and physicians in both the design and implementation processes. Convening on a regular basis helped the teams accelerate iterations. Among HCI researchers and rehabilitation physicians, (1) the wearability and portability of KnitDema, (2) testing compression elements, and (3) study protocol were among the main agenda for iteration. In particular, to identify ways to simulate edema mobilization from the hand to the upper lymphatic stream, both teams brainstormed on a fluid-based mock system that mimics the shunting of interstitial fluid outside of the closed vascular system [15].

Researchers and physicians ensured that the mock fluid system (Figure 37) provided similar fluid dynamics as the pressure applied by the device. Physicians and researchers also designed a custom volumeter unique to the hand's index finger. The teams wrote and iterated the study protocol and ran pilot studies with non-patients. In the meantime, researchers and therapists at CMC discussed the logistics of the protocol for the human subject study and patient-user experience throughout the study. With therapists, researchers refined the protocol for a smooth transition throughout each step of the study. Toward the end of the longitudinal process, physicians visited CU from WCM to test the finalized device design. This culminated in all three teams convening at CMC and WCM (Figure 34) to run a human subject study and gather insights from the patients.

6.5 Design Considerations: Towards a Personalized Rehabilitation Device

In this section, we discuss the design considerations of the system we have developed, which was based on extensive bi-weekly discussions between our research team of rehabilitation physicians and HCI researchers, regular consultation with therapists, and also a review of relevant literature [49, 74, 84] throughout a 1.5 year period.

Personalization for Individual Presentations of Edema. The pathophysiology of edema and its presentation on each patient's body can be highly individualistic. Each patient often presents a unique underlying etiology or cause of edema, which can lead to varying sorts of accompanying symptoms such as pitting-type edema, loss of sensation, pain, impaired mobility, and compromised tactile perceptions. Throughout the course of the patient's treatment, symptoms may also progress and require adjustment in treatment. Hence, the system designed should support personalized treatment catering to individual characteristics while also allowing adaptability over time.

Consideration of Compression Tolerance and Sensation. Because of varying causes of edema, it is essential to consider the tolerance to compression from different patients. Thus, the device should provide tunable compression gradients. Throughout the device development process, we stress that rehabilitation physicians on the team understand the mechanics of actuation and the mechanical properties of the materials used in the device, to provide the HCI researchers with targeted feedback for compression adjustment during the prototype iterations. Rehabilitation physicians also highlight the importance of other sensations conveyed concurrently with compression (such as heat generated from the shape memory alloy (SMA) or the sensation of tingling as SMA unloads) and make sure these stimuli are in the range of tolerable sensations. Also noted are different pain receptors with different acuity and sensitivities; the same compression magnitude could be felt more intense on the joint but mild on the glabrous finger.

Portability. Both rehabilitation physicians and therapists highlight the lack of portable treatments for edema [74, 194], despite the need for an extended period of management. Portability is a crucial factor in developing the device so that the device can be implemented in settings outside clinics without the attendance of therapists beyond the initial prescription. We seek small-scale actuators that can be integrated into the fabric and powered by a small-footprint battery while having sufficient force to compress the hand.

Comfort and Wearability. Another prominent goal is to make sure the device is comfortable and wearable. Rehabilitation physicians share how donning and doffing of pneumatic compression devices could encumber patients despite their effectiveness [82]; compression garments boast effortless donning and doffing while being less effective in mobilizing edema [74]. We aim to achieve both aspects by making donning and doffing the device undemanding but achieving active and sequential compression.

6.6 DESIGNING KNITDEMA

The KnitDema system consists of the (1) knit fabric substrate, (2) fiber-like actuators, and (3) hardware system (Figure 48). We also illustrate the envisioned patient-device experience. In this early prototype and the first step towards a personalized rehabilitation device, we center on designing an effective edema mobilization system for a single-finger-based device, which is the focus throughout the paper. We, however, envision KnitDema can be a full-hand device where the proposed compression mechanism can be applied to other fingers, the palm, and the wrist, with varying pressure outputs (Figure 48 (c)).

6.6.1 *Knit Fabric Substrate*

The knit fabric serves two purposes: (1) to wrap around the hand and enclose the fiber-like actuators, and (2) to provide passive compression to the hand. The knit substrates are fabricated on a digital v-bed knitting machine, SRY 123 SHIMA SEIKI, through the Apex 3 machine knitting software.

6.6.1.1 *Knit Structure Design*

The knit substrate is where the shape memory alloy (SMA) springs are integrated to compress the hand. We build upon the *tubular jacquard structure* [118] to integrate micro-SMA springs.

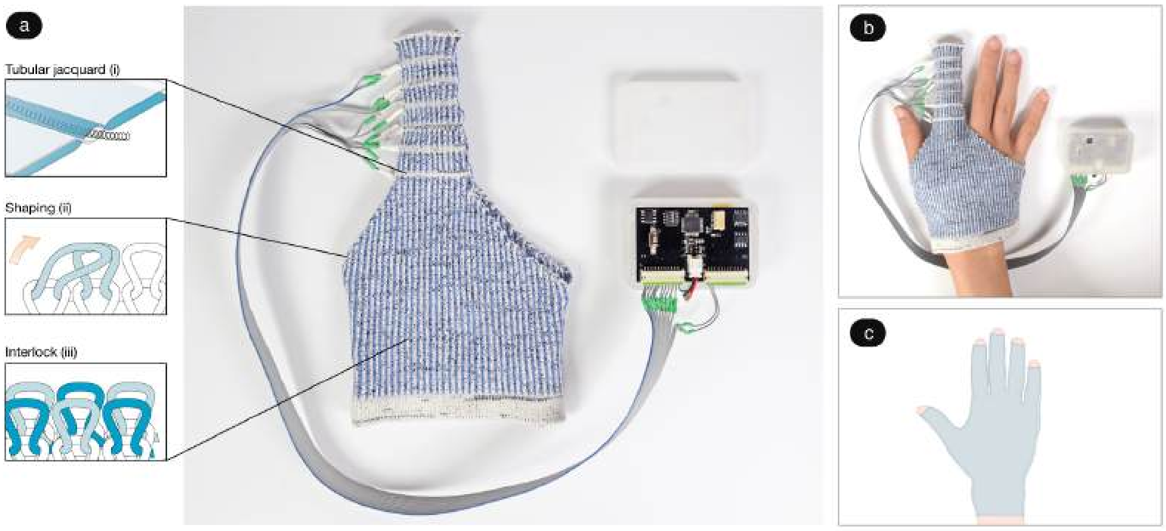

Figure 35: (a) KnitDema system in which the finger sleeve is knit with a combination of (i) tubular jacquard, (ii) shaping, and (iii) interlock structure. The tubular structure creates "channels" to incorporate SMA springs. The substrate also uses a shaping structure to conform the substrate to the rest of the fingers. (b) KnitDema finger sleeve device worn on a hand. (c) Future implementation of a full-hand KnitDema device.

The tubular structure (Figure 48 (a) i) creates hollow pockets which can run in all directions to create free-form patterns that can intersect with each other. The width of the pockets can also run as small as one stitch, or less than a millimeter, to as wide as a few inches, accommodating a wide range of actuator scales. While the active compression is provided through the integrated actuators (described in Section 6.6.2), the knit substrate affords *passive* compression. For the substrate outside the active area where the SMA springs are enclosed, we use yarns with extensive elasticity in an *interlock structure* (Figure 48 (a) iii), which exhibits constrained longitudinal strain but higher circumferential strain to help the substrate withstand enlargement of the hand. In addition, through machine knitting software, Apex 3, minuscule details of the design can be adjusted, helping size the device to varying shapes of the hand and specific body landmarks. Rehabilitation physicians pointed out that swelling could be disproportionate across the finger, making the finger base thicker than the fingertip. We used *shaping* technique via the Apex 3 to taper the finger sleeve and fit the tapered fingertips. We also used this *shaping* technique (Figure 48 (a) ii) to cover the palm and wrist while carving out an opening for the rest of the fingers.

6.6.1.2 *Passive Compression*

When the device is not actuating, a moderate amount of constant pressure is still applied to the hand. This passive compression is attributed to the knit fabric. Passive compression is a commonly administered treatment strategy in treating hand edema. Popular edema management tools that use passive compression include string wrapping, taping, Isotoner glove, or Coban wrapping [154]. Passive compression of KnitDema depends on factors including *(1) yarn properties*, *(2) knit fabric structure*, *(3) knit loop length*, and *(4) the fit of the device to the hand*. One could up the passive compression by adding yarns to the substrate. Adding additional elastic yarns leads to denser knit loops, which draw in tightly after being released from the knitting bed. Alternatively, the substrate could be knit with structures that have less ability to expand. Decreasing the loop length is another way to alter how tight the substrate is. As the lengths of the interconnected loops are shortened, the knit structure forms tighter loops, resulting in a denser structure. Finally, one could improve passive compression by sizing the device tightly to the hand. In our final implementation, we use Puma, Sting, and Jaguar yarns, sourced from Silk City. We set the loop length of the devices as 30 on the knitting machine for the desired passive compression effect.

6.6.2 *Active Compression*

For the device to serve as a compliant robotic textile and an active compression system, we consider miniaturized and small-footprint actuators that exhibit low stiffness, such that they can easily wrap around the finger and fit into the knit fabric. Prior works have used soft bladder actuators to be fitted around the limb [129, 179, 277] to apply pressure. However, these applications require inextensible layers to limit radial expansion [93, 179] or an external air reservoir that has limited portability [279]. These bulky devices pose tremendous difficulties when applied to granular areas of the body.

6.6.2.1 *SMA Spring Actuator*

Materials that contract when electrically driven, such as shape memory alloys, have been used to generate compression stimuli in haptics [83, 118]. While shape memory alloy wire demonstrates favorable flexibility and minimal footprint, the limit in its strain restricts the material's load capacity. Twisted-coiled artificial muscles (TCA) exhibit comparable linear strain [177]. However, the required temperature range for glass transition exists far outside our application. Meanwhile, shape memory alloy springs demonstrate higher load capacity for compression, affording a wide range of applications [83, 149, 160, 220, 265]. SMA springs meet our needs for a low profile, lightweight, and high energy density actuator (Kellogg Research Labs, inner diameter: 0.5mm, wire diameter: 0.25mm, transition temperature: 45C).

6.6.2.2 *SMA Integration With Knit Substrate*

Owing to free-form channels, a tubular jacquard structure can have SMA springs run through various shapes on the knit substrate. Our approach lays bands of SMA along the circumferences of the finger exerting tangential and normal forces. We explored vertical, cross, and slanted SMA configurations and compare the amount of water displaced from the pressure. The vertical configuration mobilized the most fluid with minimal energy. While one could configure SMA in complex curves to go around joints or bypass regions with dense pain receptors, our main goal is to maintain efficient load throughput [83]. As we emphasize the maximum load SMA can provide in a second, we aim to keep the energy to a minimum. Also, from a clinical standpoint, rehabilitation physicians emphasize "compression density" and more "granular compression points" to serve the device's purpose, given the tight-spaced finger geometry. All things considered, our primary focus in configuring SMA is to optimize compression density while keeping the load efficiency of each SMA maximal, which leads to the linear configuration of SMA (Figure 36).

6.6.2.3 *Sequential Compression*

The primary goal of active compression is to drain the edematous fluid captured within tissues through the lymphatic system. One of the most common treatments today involves

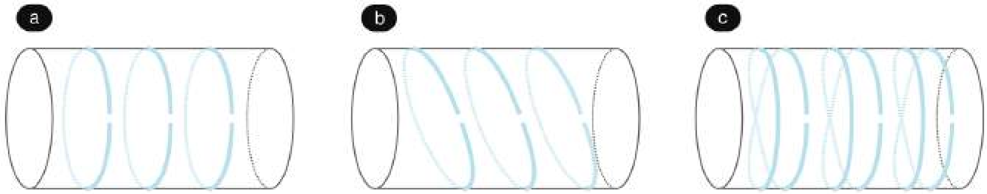

Figure 36: Each band in all configurations uses continuous SMA. As load throughput depends on the resistance of SMA, (a) is deemed the most efficient, followed by (b) and (c).

manual edema mobilization (MEM), whereby the drainage is carried out by therapists manually massaging the swollen site [102, 154]. The key principle is to massage the edematous fluid from *distal* (situated *away* from the center of the body) to *proximal* (situated *nearer* to the center of the body), in which therapists clear the pathways above the affected body areas first. It remains a time-consuming, labor-intensive, and expensive treatment to access. Another effective therapy, sequential intermittent pneumatic compression (IPC), follows the same principle: discrete chambers in a device compress the site of the problem from distal to proximal to shunt edema into veins upstream. Building on this principle, KnitDema configures several SMA spring bands dispersed evenly across the finger sleeve and applies pressure sequentially from distal (the tip of the finger) to proximal (the base of the finger).

6.6.3 *Hardware*

Our goal for the hardware design is to fulfill portability and provide a range of programmable compression intensities. We develop a rigid 51.6 x 33.8 mm printed circuit board (PCB) with the ATmega328P microcontroller. The board provides varying duty cycles through pulse width modulation (PWM), which controls 4 N-channel MOSFETs (DMN3015LSD-13) and then leads to SMA compression bands. The duration and intensity of each SMA compression band can be tuned by adjusting the PWM duration and duty cycle; different duty cycles were later used to group participants into mild, moderate, and high compression levels. We use side-entry multiple-position connectors, which are then connected to crimp connectors attached at the ends of SMA springs. A 3.7V 1200mAh Lipo battery powered the PCB. We embed the PCB and battery in separate compartments of a custom-designed 3D-printed snap-fit case.

6.7 EDEMA MOBILIZATION PARAMETERS OF FLUID DISPLACEMENT

Providing effective yet safe compression levels is critical for mobilizing edematous fluid.

To achieve optimal fluid mobilization, we conduct a series of experiments to determine suitable compression parameter values. We simulate the impact of parameters in a generalized setting. Since there are few established systems in the literature to simulate filtration and mobilization of interstitial fluid, we looked at the usage of mock circulatory loop (MCL) systems, which have been utilized to test cardiac assist devices in-vitro. These loops typically include a water reservoir, piston pump, clamp, and air-trapped water reservoir where each component mimics the left atrium, left ventricle, blood flow resistance, and vessel compliance, respectively [32]. In contrast to the native cardiovascular system, however, our inquiry was not on blood circulation but instead on the return of interstitial fluid through the lymphatic system, which is outside of and distinct from the vascular system [15].

There have been approaches to simulate shunting of edema through the movement of air bubbles in water-filled tubes lying flat [223, 267]. However, the systems proposed do not account for the displacement in the finger.

After consulting with two rehabilitation physicians and building on relevant literature, we landed on developing a mock hydraulic system where the external pressure applied to a compressible silicone finger saturated with water would drain the fluid out through a certain resistance (i.e., the tube outlet) and affect the reading of meniscus in the burette. This mock system also allowed us to observe the backflow of fluid, where the unloading of an SMA band led to immediate retraction of the fluid back to the distal of the finger. As our goal was to observe not only a single incident of compression but overall flare-ups and decreases in fluid displacement, this mock system helped us understand the trend of displacement caused by backflow. Our setup comprises a mock system with a water-saturated sponge and 3d printed bone encapsulated in the sponge, which totals the mass of an actual swollen finger. The mock finger is connected to a narrower tube, which is then connected to a burette such that the meniscus fluctuates as the pressure begins and diminishes (Figure 37).

Parameters for active compression, which influence fluid mobilization, include **PR1: Band Interval**, representing the time interval between single instances of SMA band compression,

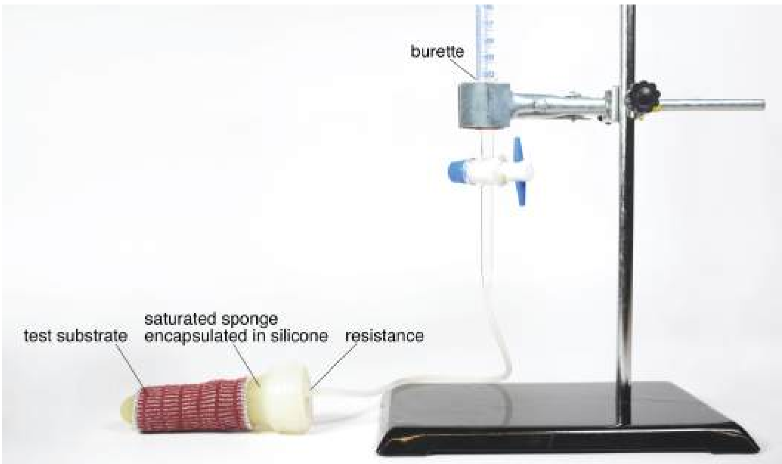

Figure 37: Setup to simulate compression parameters. Pressure applied to the mock-up finger drains the water out of the finger and into the burette.

PR2: Sequence Interval, the time interval between completed sequences of SMA compression, **PR3: Compression Duration**, the duration of each SMA band compression, and **PR4: SMA Band Number** the number of SMA bands. These parameters are tested in a non-factorial method and in the above order. Starting with 3 SMA bands, tested first were the Band Interval (PR1) and Sequence Interval (PR2). Subsequently tested was the Compression Duration parameter (PR3). Finally, we tested the SMA Band Number (PR4) with identified aforementioned parameters. For clarification of the terms, *SMA band* represents a single SMA spring around the circumference of the finger; a *sequence* denotes the completion of one full compression cycle of all SMA bands in the fabric substrate; *interval* represents the unloading period between preceding and subsequent actuation of SMA; *compression instance* is in which an SMA band compresses for a given period of time. A summary of our finalized set of parameters can be found in Table 3.

6.7.1 *Compression Interval Parameters (PR1, PR2)*

In edema compression treatment, fluid *backflow* can occur between compression instances. Backflow is a phenomenon where the fluid displaced from the distal location refluxes back to the distal when the pressure unloads. We aim to minimize backflow as much as possible. To examine the backflow between individual SMA bands compression and between complete sequences, we define *band interval* as an unloading period between each SMA band compression; and *sequence interval* as an unloading period between a complete activation sequence of all SMAs. Here we run a factorial test, in which we activate each of 3 SMA bands for 30 seconds, repeating 12 sequences, with/without 30-second *band interval* and 30-second *sequence interval*. The result reports that the most effective compression is when neither *band interval* nor *sequence interval* is present (Figure 38).

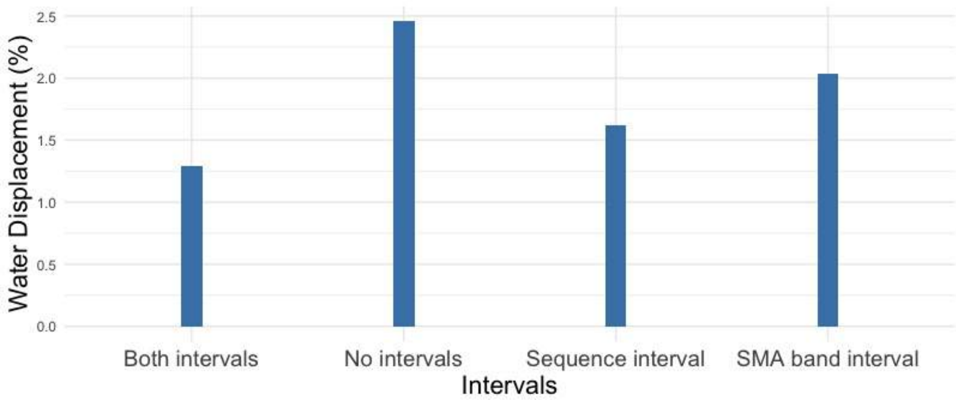

Figure 38: The result is most effective without any intervals, meaning when SMA applies pressure incessantly.

6.7.2 *Compression Duration Parameter (PR3)*

After eliminating *band interval* and *sequence interval*, meaning SMA bands contract continuously one after another, we examined how the duration of SMA loading affects fluid displacement. In our setup, we power each of the 3 SMA bands from 15 to 165 seconds in increments of 15 seconds (total elapsed time for 3 SMAs between 45 - 495 seconds). The result shows that powering 3 SMA bands for 105 seconds drains fluid the most (Figure 39). While 105 seconds distinctively outperformed others, this result is specific to the setup under 3 SMA bands due to the non-factorial setup.

6.7.3 *SMA Band Number Parameter (PR4)*

Our next parameter in question is whether a certain number of SMA bands transfers water more effectively than others. Building on the previous results, we start by powering 3 SMA bands for 105 seconds each without intervals between compression instances and sequences.

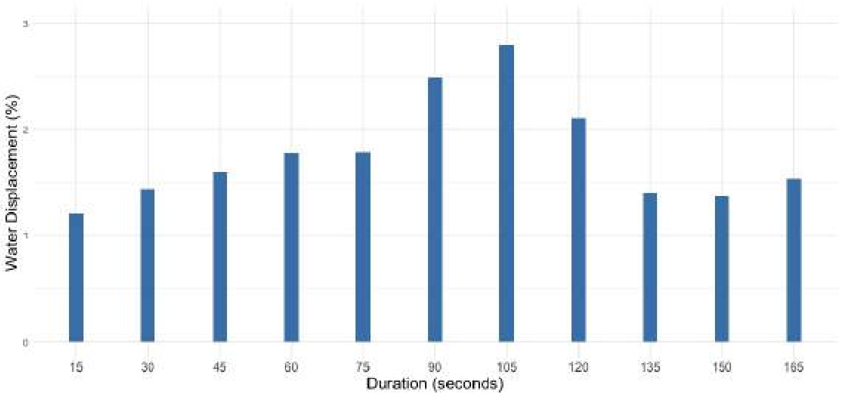

Figure 39: Influence of the duration of each SMA compression on water displacement. Three SMA bands compressed the finger prototype from 15 seconds to 165 seconds each. 105 seconds of compression mobilized 2.8% of water.

The number of SMA increments from 3 to 10. We notice that the amount of water transferred peaks at 6 SMA bands, with the result of more than 9% of displacement (Figure 40).

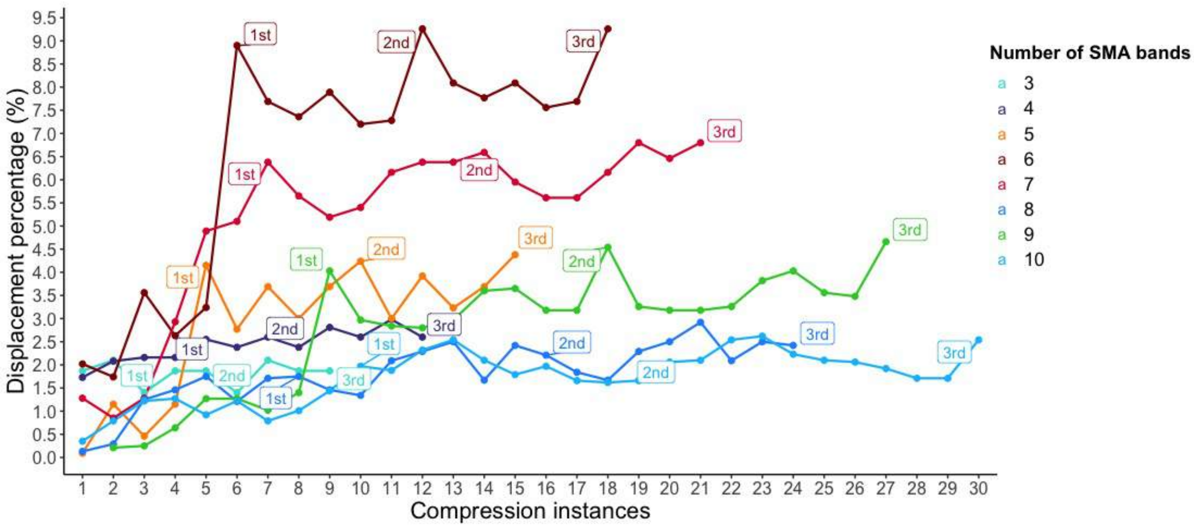

Figure 40: Simulation of the impact of SMA number on water displacement. The number of SMA bands in one substrate varied from 3 to 10, as labeled in the legend. All SMA bands ran their course three times, thus resulting in different numbers of compression instances in total. For instance, 7 SMA bands would result in 21 instances in total by the end of the operation; 5 SMA bands, 15 instances. The labels denote the end of each sequence (e.g., *1st* denotes *the end of 1st sequence*). When six SMA bands ran the full three sequences, they displaced the most fluid, more than 9% (see label *3rd* of line *6*).

Number of SMA band	Compression duration	SMA band interval	Sequence interval
6 SMA bands	105 seconds	X	X

Table 3: Finalized parameters for active compression.

6.7.4 *Resulting Edema Mobilization Parameters*

In summary, we simulated parameters that dominated fluid displacement and finalized the parameters in Table 3. The finalized parameters formed the basis of the KnitDema design and the study protocol.

After we characterized the parameters, HCI researchers and rehabilitation physicians discussed the implications of the compression parameters in practice.

Before we deployed the device in the user study, clinicians visited CU and tested a device programmed with the resulting compression parameters to provide assurance from a clinical perspective that the device would deliver a perceivable amount of compression without causing potential discomfort to an end user.

6.8 FEASIBILITY CASE STUDY

The goal of our human subject case study is to (1) understand the feasibility and safety of the device on patients with hand edema, (2) observe how participants interact with and perceive the device during the treatment, and (3) generate directions toward achieving the potential efficacy of the device. We format human subject case studies to obtain quantitative and qualitative data. To study the feasibility and potential efficacy, we introduce three phases to the study, in which we modify the compression levels from mild to moderate to high (Figure 41).

6.8.1 *Participants*

We recruit 5 hand edema patients through CMC and WCM. CMC is a regional rehabilitation clinic that offers hand therapy and lymphedema management programs. WCM is a medical institution with a rehabilitation outpatient clinic that provides physical and occupational therapy, where therapists see patients with various diagnoses, including stroke and brain and spinal cord injury. The ages of the participants range between 39 to 69, and their primary method of therapy included MEM by therapists. While some receive care more frequently than others, the maximum frequency is usually capped at twice a week. We recruit patients with various diagnoses after the screening process; all patients present with one or more swollen fingers, excluding the thumb (Table 5). The participants are not randomly assigned or stratified to the compression levels. Instead, participants first test the lowest level of compression, after which physicians determine the level of compression increments based on the patient's edema condition for safety considerations.

6.8.2 *Apparatus*

While retaining the finalized compression parameters (Table 3), we size each device to the measurements of the patient's hand. With insight and testing by the rehabilitation physicians, we set devices' compression into three levels—mild, moderate, and high—to identify the relationship between these compression levels and the reduction of swelling. These compression levels are determined by pulse width modulation (PWM), which is the duty cycle of the voltage that dominates the load throughput of SMA springs. Higher PWM leads to higher load throughput. The varying specs of each device follow this table (Table 4). All devices have a single sleeve for the index finger and identical SMA springs (wire size 0.25mm, mandrel: 0.5mm, transition temperature: 45°C (113°F)). We fabricate devices using Puma, Sting, and/or Jaguar yarns, all sourced from Silk City. To fit a device to hands with various degrees of swelling, we collect six anthropometric measurements of the hand in the pre-study survey: (1) length of the index finger, (2) circumference of $\frac{1}{3}$ distal to the base of the finger, (3) circumference of $\frac{2}{3}$ distal to the base of the finger, (4) circumference of the base of the finger, (5) circumference running from the thumb MCP to the pinky MCP, and (6) circumference of the wrist.

Patient Code	Substrate Materials	Loop Length	Compression Level
P1	Puma, Jaguar, and Sting	30	Mild
P2	Puma, Jaguar, and Sting	30	Mild
P3	Puma and Sting 2 ends, and Jaguar	30	Moderate
P4	Puma and Sting 2 ends, and Jaguar	30	Moderate
P5	Puma and Sting 2 ends, and Jaguar	30	High

Table 4: Specs of devices customized for patients.

Code	Age	Gender	Standard of Care	Care Frequency	Care Site	Home Maintenance
P1	69	F	MEM, IPC, CG	2 times a month	CMC	IPC, self-massage
P2	39	F	MEM	2 times a month	CMC	N/A
P3	53	F	MEM, hand therapy	2 times a week	CMC	Self-massage
P4	68	M	CG, taping, OT	2 times a week	WCM	CG
P5	69	M	MEM	Once a week	CMC	Exercise, self-massage, ice

Table 5: Participant information gathered through a pre-study survey. MEM: manual edema mobilization by therapists; IPC: intermittent pneumatic compression device; OT: occupational therapy; CG: compression glove.

6.8.3 *User Study Protocol*

The user study protocol consists of the following steps: (1) a pre-study survey, (2) pre-intervention measurements (baseline), (3) intervention, (4) post-intervention measurements, (5) a 7-point Likert scale post-study survey, and (6) a semi-structured interview.

Pre-Study Survey (10 minutes). We conduct a remote pre-study survey 1-2 weeks prior to the intervention. Here we ask patient's demographic information, the standard of care, and the measurements of the affected hand (Section 6.8.2). We start customizing KnitDema devices based on anthropometric measurements.

Pre/Post Intervention Measurements (30 minutes each). To assess the influence of the intervention, we conduct three measurements on the affected hand before and after the intervention. The pre-intervention measurements represent the baseline, for which we measure finger volume, finger circumference, and range of motion (Figure 42). To maintain consistency, all measurements are repeated 5 times by an observer [33, 35, 134] while the order of measurements is randomized.

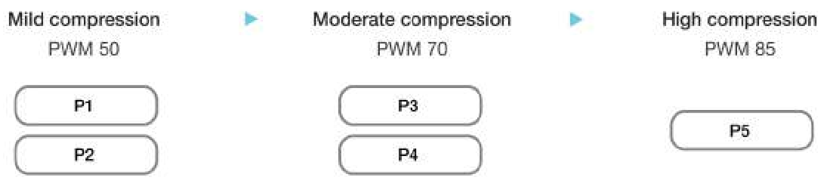

Figure 41: User study timeline and patient assignment to compression levels. Pulse width modulation (PWM) determines the voltage's duty cycle and the compression's intensity.

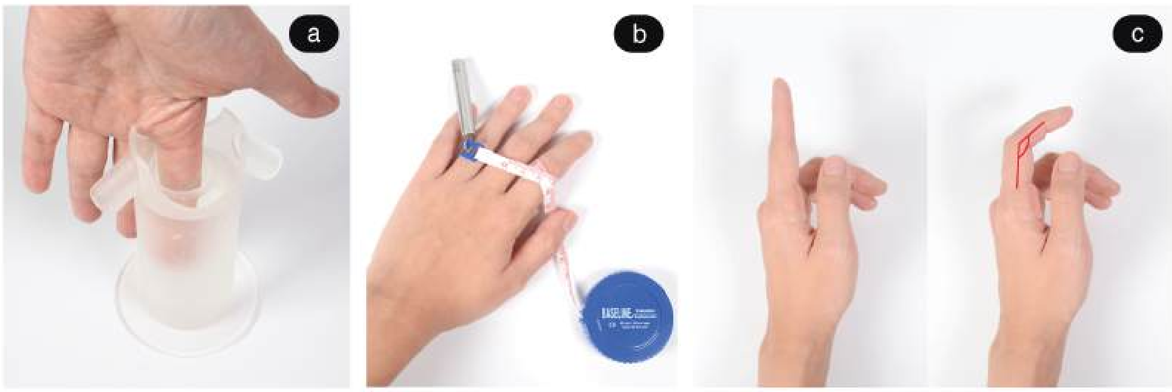

Figure 42: (a) volume measurement, (b) circumference measurement, and (c) range of motion (ROM). ROM measures the internal angle of flexion.

- **Volume Measurement**: this method quantifies the volume of the affected finger by submerging it into a tank filled with water and measuring the weight of water displaced from the tank. We mark the base of the finger and align the water surface to the mark for consistency. To carry out the accurate volumetric measurement, we custom design a 3D printed volumeter that can accommodate the web space between the index and middle finger and has a fixture inside to guide the position of the finger as it submerges (Figure 42 (a)).

- **Circumference Measurement**: we measure the circumferences of the distal interphalangeal joint (DIP), proximal interphalangeal joint (PIP), and the base. We also leave marks on the joints for consistent measurements. We repeat this measurement 5 times for each joint (Figure 42 (b)).

- **Range of Motion (ROM)**: We measure the flexion of PIP. We ask participants to perform two motions: (1) straighten the finger, and (2) flex the finger as much as possible. We repeat the motions 5 times while recording them. We use a computer goniometer to obtain angles from the videos. We measure the internal angle of the DIP - PIP - MCP (metacarpophalangeal) joint (Figure 42 (c)).

Intervention (60 minutes). We model the duration of the intervention after one-hour regular therapy sessions participants receive. As the intervention begins, we take pictures of the hand as a comparison point (Figure 43). Participants wear the device on their own. We ask participants to position their hands on the desk slightly below the heart level. Once they don the device, the device exerts 105-second pressure on each of the 6 SMA bands for 5 sequences, totaling 52 minutes and 30 seconds ($105 * 6 * 5$). This duration of the intervention was determined by therapists and rehabilitation physicians on the team in consideration of MEM therapy duration in clinics, which is typically under an hour, without breaking up the compression sequence. Upon the completion of the intervention, participants take off the device, and we take pictures of the hand to compare the hand visually.

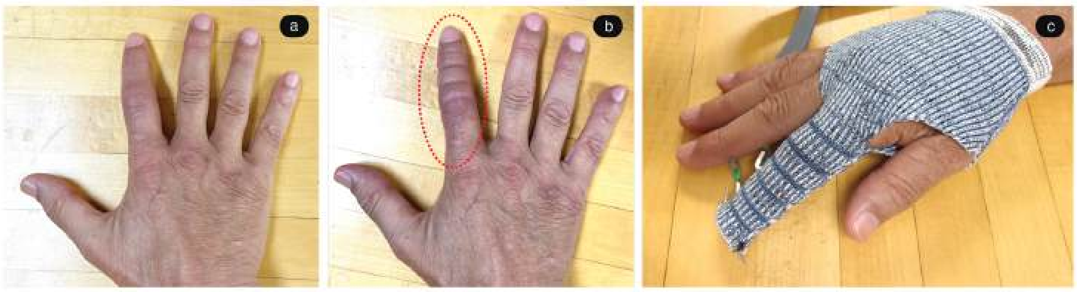

Figure 43: Photographs of a participant's hand before (a), and after (b), the intervention (c). Marks from intervention indicate that the pressure is palpable and the device fits the finger snugly.

Post-Study Survey (5 minutes). On completion of the intervention and post-intervention measurements, participants respond to a set of 7-point Likert scale questionnaires on wearability, sensation, and comparison with the standard of care. The survey segues to the subsequent semi-structured interview.

Semi-Structured Interview (20 minutes). To delve into the questions participants answer in the post-study survey, we interview them in a semi-structured format. Key themes of the interview inherit the items from the previous survey: the wearability of the device, the sensation of compression and heat, and the comparison with the standard of care.

Measurement	ICC of baseline	ICC of post	95% CI of baseline	95% CI of post
Volume	0.985	0.99	[0.948, 0.998]	[0.965, 0.999]
Circumference of DIP	0.969	0.949	[0.898, 0.996]	[0.839, 0.994]
Circumference of PIP	0.983	0.986	[0.943, 0.998]	[0.952, 0.998]
Circumference of base	0.967	0.987	[0.892, 0.996]	[0.957, 0.999]
ROM	0.99	0.992	[0.964, 0.999]	[0.973, 0.999]

Table 6: Intra-rater reliability of measurements and CIs. ICC score close to 1 indicates high similarity between measurements.

6.8.4 *Analysis*

We analyze intra-rater reliability to take into account the multiple measurements (5 times each for the three measurements) carried out by a single observer (Table. 14). For the intra-rater reliability, we use the intra-class correlation coefficient (ICC) in R [190]. We take into account the non-independency of data across participants through the linear mixed effects model [91, 255] and *lme4* [18]. Through visual inspection, we confirm normal distribution and constant variance of residuals for all three datasets: *volume*, *circumference*, and *ROM (range of motion)*. In analyzing *circumference*, we anticipate three random effects: (1) **participants**, (2) the *interaction* between **participants** and **measurement times**, and (3) the *interaction* among **participants**, **measurement times**, and **finger joints**. We anticipate random effects of two factors for the rest of the measurements: (1) **participants**, and (2) the *interaction* between **participants** and **measurement times**.

Audio recordings of the semi-structured interviews are manually transcribed to identify salient themes. All qualitative data undergo iterative coding, which is conducted independently by two experienced researchers. We use codes with a reasonable degree of agreement among the coders to identify salient themes based on thematic analysis [27].

6.8.5 *Results*

Here we present results from the case study. For the case study, we report ICC scores, 95% confidence intervals for pre-measurements (baseline) and post-measurements (Table 14), significant outcomes, and descriptive graphs.

Volume Measurement. Linear mixed effects model reveals no significant changes before and after the intervention. In the descriptive data, a decrease in the volume is deemed favorable as it indicates edema drained. The red lines are indicative of an increase in the finger volume; the green lines represent a decrease in the finger volume. In percentage, the finger volume changes before and after intervention by +4.3%, +1.7%, -2.7%, -10.3%, and -3% for the respective participants. P4 demonstrates the largest decrease in the volume. What is notable in the volume measurement is that the participants in moderate and strong compression levels show a favorable amount of reduction in swelling (Figure 44).

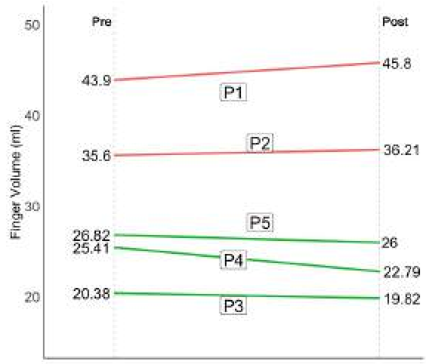

Figure 44: Changes in the finger volume before and after the intervention, labeled by participant code. Red indicates an increase, and green indicates a decrease in the volume.

Circumference. The model analyzes that the differences in the circumferences across DIP, PIP, and the base joints are significant (p-value $< .001$). However, we fail to observe significant changes in the measurement before and after the intervention. As for descriptive data, we consider the decrease in the circumference a sign of favorable results. As before, the green lines indicate a decrease in the measurement while the red represents an increase in circumference. P5 shows noticeable decrease of 4.1% in circumference on average, followed by P4 (-1.9%), P1 (-1.1%), P3 (-0.3%), and P1 (1.1%). As for the circumferences of the joints, DIP changes by -2.2%, PIP -1.5%, and base -0.5%, showing a diminishing tendency in general from distal to proximal (Figure 45).

Range of Motion. Literature suggests that the success of manual edema mobilization is correlated with an increase in the range of motion [188]. Our analysis shows no significant changes in ROM before and after the intervention. Descriptive data informs that the green lines indi-

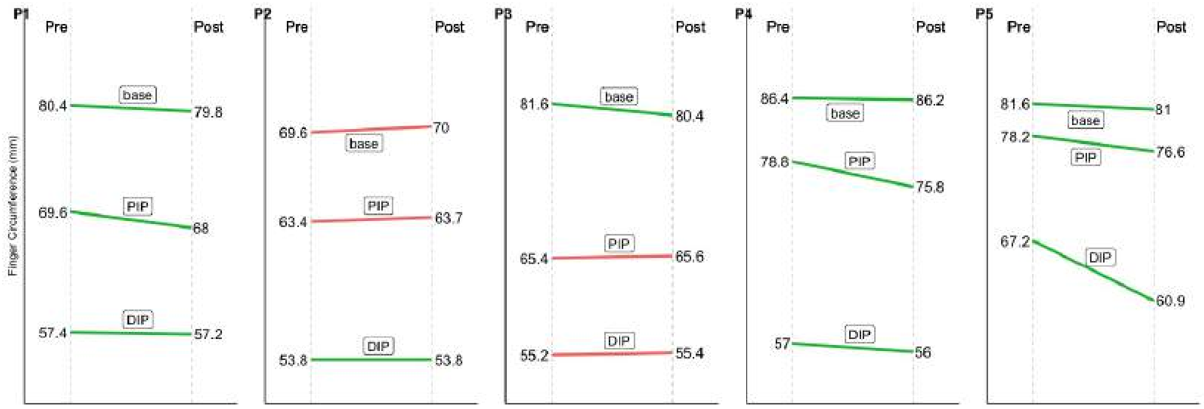

Figure 45: Changes in the circumference of the DIP, PIP, and base, before and after the intervention. Red indicates an increase, and green indicates a decrease in the measurement.

cate a decrease in the flexion angle, which is deemed favorable, while the red lines indicate an increase in the range of motion. ROM is where we observe a high level of variance among the patients due to underlying medical conditions, as some participants who have their mobility compromised have difficulty flexing their fingers. Participants, on average, show a decrease of 1.7% flexion angle after the intervention, which is deemed favorable (Figure 46).

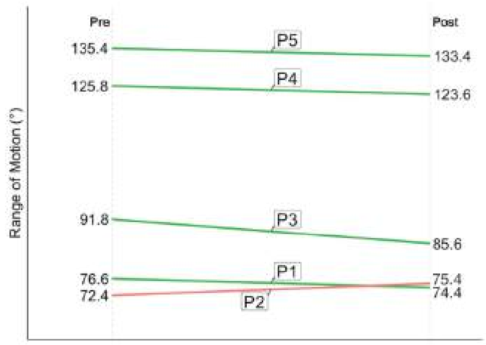

Figure 46: Changes in the range of motion in degrees (°) before and after the intervention, labeled by participant code. Red indicates an increase, and green indicates a decrease in the internal angle of flexion.

Post-Study Survey and Semi-Structured Interview Findings.

The post-study survey revealed insights into how participants interacted with the device and formed the foundation of our semi-structured interview. In this survey, we asked eight 7-point Likert scale questions on the themes of **wearability**, **sensation**, and **comparison with the standard of care**. This was followed by a semi-structured interview where we expanded on these themes for each individual's experience.

- **Wearability**: On the Likert scale (1: extremely uncomfortable, 7: extremely comfortable), participants rated the donning and doffing process with a median score of 6. There was consensus that the knit substrate made donning and doffing of the device comfortable. This comfort was also observed during the intervention, obtaining a median score of 6 (1: extremely uncomfortable, 7: extremely comfortable). Participants pointed out that "It was very, very light. I couldn't even tell if it was on. It was comfortable, but it didn't over squeeze." (P1). The knit's materiality was also positively associated with wearability: "It wasn't sticky on the skin" (P1). Participants also reported that they became accustomed to the device throughout the intervention process (median score 6. 1: strongly disagree, 7: strongly agree). On the other hand, participants attributed most of the factors that constrained wearability to the exposed wires in the current prototype and the 3D-printed enclosure and expressed a desire to integrate everything into the fabric glove. Because the SMA springs were connected to the enclosure, some pointed out that the wires could catch onto objects and might get in the way. They suggested we integrate the wires into the glove. "I'd tuck them (wires), so you didn't have to have them around." (P3). "Only issue was when the wires are coming out." (P5). P5 mentioned that the hardware could also be integrated into the fabric: "you could put that (enclosure) right into the glove." (P5)

- **Sensation of compression and heat**: Unlike the overwhelming consensus towards wearability, participants varied on their perception of compression. On the question asking if they perceived compression evenly across the finger, they rated a median score of 2 (1: highly clustered and 7: highly distributed). During the interview, it was plain to see that most participants did not perceive pressure evenly across the finger due to various reasons. While P3 noted the compression was felt "towards the finger base," for P2 and P4, the compression was more vivid on the joints. P2 mentioned experiencing compression "towards bony rather than fatty areas." P4 mentioned mostly feeling "strain on the joint." On the other hand, P5 perceived compression steadily and evenly across the length of the finger. Rehabilitation physicians on our research team reflected that this might be due to different etiologies impacting individual tolerances toward pressure. Several participants (P2, P3, P5) perceived the sequential compression to be moving in a certain direction. Besides compression, another sensation was slight heat. However, it did not cause discomfort. All participants experienced a slight degree of heating regardless of compression levels: "definitely had the warmth." (P3), "there was heat besides compression." (P4), and "here is slightly warm." (P5).

Other described sensory stimuli that accompanied compression were "a little twinge" (P2) and "pulsing" (P5). Regardless of the experienced sensation, it did not cause discomfort to the level requiring a change in posture during wear (median: 7, 1: change posture all the time, 7: not at all).

- **Comparison to the standard of care**: Participants were neutral on the appearance of the device (median: 4, 1: strongly disagree, 7: strongly agree). However, they found the device barely awkward despite the unconventional form factor (median: 2, 1: strongly disagree, 7: strongly agree). Participants seemed to enjoy silent actuation compared to the pneumatic compression counterparts: "(the device) doesn't make noise. It's very quiet." (P1). They often preferred the reduced bulkiness over the pneumatic compression device: "it's less bulky." (P1). Participants who received manual edema mobilization as primary treatment noted that the device could provide equal compression across the perimeter. They perceived compression "equally around the finger." (P2), while therapists would massage less evenly with their fingers: "It's the thumb, index and the middle fingers, so you're not getting the whole ring whereas your device is actually working the entire ring around the finger." (P3). Participants who used compression garments commented that too much pressure would fatigue their hand, "I get totally waffly." whereas KnitDema was "soft compression" and "equally around the finger." (P2). Adding to the responses, P5, who received taping treatment, referred to the device as "steady" compression compared to taping. P5 noted that taping treatment could be "uneven" and result in cramps (P5).

- **Potential as a remote treatment device**: Participants were positive concerning KnitDema's potential as a future treatment device. Participants rated a median score of 5 regarding if they could see themselves wearing the device in their everyday lives (1: strongly disagree, 7: strongly agree). It was shared among the participants that the "full glove would be really helpful." and that "if it were portable [I would] bring it to work." (P2). Many expressed interest in using the device during sleep so the swelling would subside in the morning: "it would be absolutely wonderful if you could wear it to bed." (P3). P5 mentioned the device could offer programmability of the compression as needed, "I think the ability to program compression [is helpful] because I think it was a little too light." (P5). Many noted that they would put the device to use in during pockets of time: "lunch break" and "watching TV" (P5), or "I'd use it while reading." (P1). These responses highlighted how participants were eager to make use of scrap time for treatment to help swelling diminish. The interview also shed light on potential areas for improvement. Among the concerns was the possibility of the wires disconnecting while using it in public, "anytime you have electronics on the outside, you're gonna be afraid of, like, disconnecting." (P2).

6.9 DISCUSSION

This research discusses the mechanism of sequential compression for swollen hands evolving into a working system and being deployed in human-subject user tests. The device has proved its feasibility and comfort, alongside the possibility of a take-home telehealth device, thanks to its portability. However, the device leaves room to improve its potential efficacy and explore possible compliance issues over mid or long-term use. Moreover, current device fabrication encourages lowering the barrier of fabrication through a comprehensive pipeline. This is detailed in the following sections.

This research engaged two distinct disciplines: human-computer interaction and rehabilitation medicine, in which the co-design process helped close the gap and establish a shared intellectual ground. Below, we reflect on the insight gathered from each domain.

Clinical Insight on the Co-Design Journey. Co-design involved physicians in multiple aspects of the research from the onset. Designs and device iterations have evolved throughout the co-design process following clinical insight and acumen. From a clinical perspective, KnitDema's co-design held significance because it welcomed the physicians to be "involved in the process of *designing*, whereas usually, the completed device is what is given to us." Physicians also received firsthand feedback on the device during the user study, which helped them notice ranging perceptions of "compression" and "patients' tolerance to pressure, warmth, and other factors." Hearing how patients "compared the ease of use of the device to other hand edema techniques" gave physicians insight on where to situate KnitDema on the spectrum of treatment devices. Physicians and therapists expressed that translating the edema mobilization technique into automated textile motion would not have been possible without the initial stage of expertise exchange for grounded understanding between disciplines.

HCI Research Insight from the Co-Design Journey. From an HCI research standpoint, the development of the KnitDema system benefited from multi-faceted insight from both the rehab physicians and physical & occupational therapists (PT/OTs).

Rehabilitation physicians provided insight from a diagnostic and physiological standpoint. Physicians' insight was valuable in the early development and validation of the mock fluid displacement system and our custom volumeter. On the other hand, the PT/OTs provided practical insight into the patient experience based on their first-hand therapy engagement, which was critical to our study protocol design. They bore witness to how external factors such as seasonal changes in humidity, temperature, and hand usage in daily activities could aggravate swelling and congestion, which would have been dismissed without frequent interaction with the patients. Their firsthand experience motivated us to design a device that can be integrated into a patient's daily life.

Establishing Coordination in Multi-Site Research. In retrospect, working across institutions required a great deal of coordination and communication. We learned that if a study aspired to involve human subjects in deploying therapeutic devices, the first step would be establishing logistical coordination between the institutions. For example, if the institution that runs the study was not affiliated with the Investigator, one must comply with the other institution's review board and tailor the protocol and Informed Consent accordingly. Once the coordination has been established, subsequent steps would include (1) setting forth shared research goals, (2) providing a clear research timeline and expected roles of each entity, and (3) providing concrete ideas of deliverables through frequent communications.

6.10 CONCLUSION

We present the design and development of KnitDema, a digitally knit robotic textile that is individually programmable for sequential compression across finger phalanges for mobilizing hand edema. With rehabilitation physicians and therapists, we adopt a co-design method throughout the design, development, and implementation phases of the project. We simulate KnitDema's compression ability and test parameters that determine the effectiveness of active compression. Drawing from the results, we design the device with parameters that effectively shunted fluid. We conduct a case study of KnitDema with 5 persons with edematous hands to obtain a qualitative and quantitative understanding of device feasibility. Measurements of volume, circumference, and range of motion demonstrate the feasibility and potential efficacy of KnitDema. The semi-structured interviews highlight the wearability of the device, participants' perceptions of compression, how the device compares to other standards of care, and KnitDema's prospects as a personalized device for treating hand edema. This project sheds light on the potential of using the under-explored advantages of robotic textiles as a *personalized* rehabilitation tool that is inexpensive to manufacture and comfortable to wear.

6.11 POSITIONING KNITDEMA WITHIN THE DESIGN SPACE

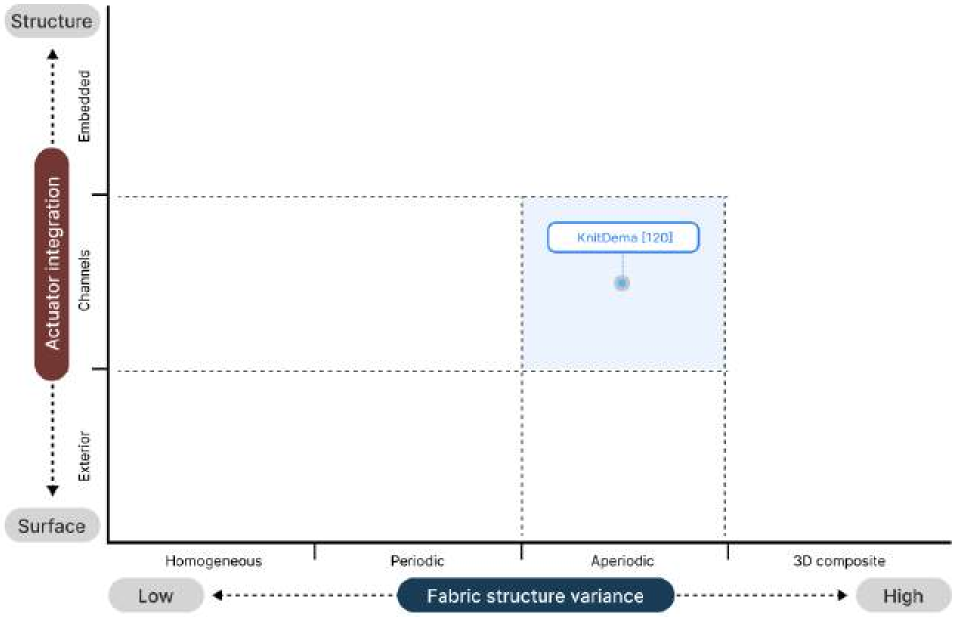

Figure 47: Situating KnitDema in the design space.

KnitDema distinguishes itself in the design space by its emphasis on personalized form factor. It is tailored specifically to the anatomical location it covers as well as the unique physical attributes of each user, made possible by fine-tuning through *aperiodically* arranged knit structures that would be challenging with other fabric manufacturing techniques.

The device's ability to apply pressure while conforming precisely to partial hand is achieved by incorporating nitinol actuators into fabric *channels* preserving the inherent property of fabric substrates (Figure 47). Such use of digital knitting techniques contributes to the application of robotic textiles in medical and therapeutic settings.

6.12 phase 2: mediknit—soft medical making tool

While digital knitting offers significant advantages for the fabrication of textiles with enhanced conformity and ease of integrating actuators, it is important to note that the fabrication process remains complex and non-intuitive. This complexity limits other potential designers who could bring expertise in their domains, thereby restricting robotic textile fabrication's broader adoption and democratization.

In response to this challenge, in this chapter, a design tool was developed to facilitate a more intuitive approach to designing wearable robotic textiles through digital knitting. This tool allows designers to input the hand geometry of a target user to generate a two-dimensional template of the expected device. The tool then superimposes the 2D template onto a photo of the user's hand. These superimposed images indicate the precise locations of the actuators, enabling designers to customize the design according to the unique body shape of each individual. This approach ensures a better fit and more effective performance of the robotic textile, tailored to the specific needs and dimensions of the user.

This chapter lays out a case study and illustrates the implementation of the design tool with a group of clinicians who had no prior training in digital knitting. Despite their lack of specialized knowledge in textiles, these clinicians successfully customized devices to fit three patients with edematous hands. Although the resulting device does not transition (move up or down) the scales of the parameters within the design space and inherits the form factors of KnitDema, this case study demonstrates the potential of the design tool. It shows how the design interface can make the process of creating robotic textiles more accessible, even for those without technical expertise in digital knitting. This highlights the tool's capability to democratize the design and customization of wearable robotic devices, paving the way for broader adoption and personalized solutions in the field.

The creation of the MediKnit device and the associated design tool was a team effort involving Narges Pourjafarian and Arhan Choudhury from Cornell University, along with Joan Stilling from Weill Cornell Medicine, under the guidance of Cindy Hsin-Liu Kao. Narges Pourjafarian and Arhan Choudhury led the development of the accessible software design tool for personalized therapy. Throughout this chapter, I will use "we" to denote our collaborative work in developing the device. The information presented is based on a paper that has been accepted to IMWUT '24, for which I am the primary author, titled "MediKnit: Soft Medical Making for Personalized and Clinician-Designed Wearable Devices for Hand Edema.".

6.13 INTRODUCTION

The emergence of diverse fabrication tools and techniques holds promise as they can offer healthcare professionals tools to deliver healthcare products at the time of care. This helps different domains of knowledge blend smoothly with the larger world of ubiquitous computing.

Medical making, coined by Lakshimi et al, is born out of an attempt to use technical fabrication processes and 3D printable materials in the medical field [128]. This concept underscores the accessibility of digital fabrication for occupational therapists (OTs), physical therapists (PTs), and clinicians to engage with these tools [97].

However, the current process for the development of medical devices is characterized by certain limitations. First, it focuses on the production of monolithic and inflexible devices through 3D printing technology, which restricts applications to rigid devices for orthotics or rigid contraceptives [97]. Inflexible and clunky medical contraceptives are not well suited for treating conditions that manifest in the body parts with intricate shapes (e.g., fingers), which necessitate soft and malleable devices. Secondly, the current framework does not demonstrate the capacity to customize devices, a crucial feature for addressing medical conditions, such as acute edema, scoliosis, and Duchenne muscular dystrophy, that manifest with extensive variability across individuals. Thirdly, current medical making lacks adaptability and clinician-led design input during the fabrication process, resulting in repetitive refinement processes at the cost of wasting both clinicians' and patients' resources and time. The cumulative effect of these limitations restricts material choices to rigid 3D-printable ones, lacks customization, and delays the delivery of medical devices.

To make a tangible case of how the current medical making is incompatible with certain medical conditions, we focus on hand edema. Hand edema not only varies in degrees and progressions [75] but also encompasses diverse hand shapes. 3D-printed devices cannot effectively compress edematous hands, and clinicians' input to address variability and personalize therapy is required for hand edema.

Nonetheless, the existing method of treating edema lacks personalization, leaning heavily on pre-made pneumatic compression devices. Customized therapy is currently limited to manual massages administered by therapists in clinical settings [153, 154], necessitating in-person appointments and resulting in exorbitant costs. This is where the portable device and personalized fabrication can benefit all.

In response to challenges posed by the current medical making and edema treatment, we introduce the concept of *soft medical making*. This approach utilizes textiles as the primary material, streamlining customization and allowing for design adaptations. By bridging the textile manufacturing process, which, due to machinery complexity is typically reserved for experienced textile technicians, with clinical domains, we aim to offer a new medium for healthcare providers. We exemplify this concept of *soft medical making* through MediKnit, addressing the needs of patients with hand edema. MediKnit consists of an accessible design tool for the personalization of devices, providing visual representations and allowing real-time adaptation. Through this process, clinicians fine-tune designs to meet individual clinical requirements. The fabrication process was characterized by rapid turnaround and fewer iterations. MediKnit devices include a machine-knit glove with active compression, produced with the assistance of our design tool, and a hardware system enabling compression control through a custom printed circuit board (PCB). Finally, we deploy these personalized devices and conduct a user study with six participants presenting hand edema. Our case studies demonstrate the potential of soft medical making to broaden accessibility and enable personalized, adaptable, and clinician-led fabrication of medical devices, benefiting both patients and healthcare providers.

By introducing the MediKnit design tool and devices, our work presents textile-based medical devices that are: 1) *personalized* to each patient, addressing the variability of symptoms and hand shapes, 2) *portable* to eliminate patients' commutes to clinics, and 3) *cost-effective*, with a manufacturing cost of 85 USD. Our work extends to the design process by empowering clinicians as active medical decision-makers, encouraging them to integrate their domain knowledge and tailor devices to meet the distinct requirements of each patient. This clinician-led design approach streamlines iteration time and enhances the overall design process for such devices, offering benefits for both patients and healthcare providers. In summary, the main contributions of this paper are:

- **The development of an accessible design tool for personalized therapy:** MediKnit, an accessible soft medical making design tool and the resulting personalized edema device. MediKnit design tool minimizes technical requirements for the fabrication of textile-based devices. Our tool emphasizes personalization, allowing customized solutions tailored to individual needs and anatomical characteristics. The resulting MediKnit device is delivered timely without the need for iterative adjustments.
- **The development of adaptive design workflows with clinicians as medical decision makers:**

  The MediKnit design tool allows an adaptive workflow by actively involving healthcare professionals as contributors. Clinician-led design ensures that devices are precisely tuned to clinical requirements, enhancing their effectiveness.
- **Description of case studies and a user study:** To demonstrate the practical application of our approach, we use case studies focused on hand edema. These real-world scenarios serve as tangible examples, highlighting the practical implementation and advantages of the proposed "soft medical making" process. The evaluation of the resulting devices is conducted through a user study, where we gather insights directly from patients. By combining both case and user studies, we obtain valuable insights into the adaptability and effectiveness of our soft medical making approach.

6.14 BACKGROUND: HAND EDEMA

Edema results from fluid buildup due to various causes, affecting different body parts, including the hands and feet. Edema in the hands and feet, presents additional challenges as they are at the distal end of the lymphatic system, and have varying shapes. The current standard treatment for hand edema lacks personalized therapy, relying on labor-intensive retrograde massage or standardized pneumatic devices [154].

Massages are effective but can be costly, ranging from 50 USD to 150 USD per session [193]. Pneumatic sleeves, with proven efficacy [154], are priced between 300 USD to 700 USD but do not cater to intricate extremities like hands, fingers, feet, or toes—common areas affected by peripheral edema. Considering the diverse nature of edema and the shortcomings of existing treatments, there is a pressing need for personalized approaches to address the wide variability in this condition. Given the pervasive negative impacts of edema, numerous clinical studies have explored treatments from a medical standpoint, assessing readily available methods with patient involvement (Table 7). Our approach involves multiple stakeholders, offering a broader range of perspectives from the recipients (i.e., patients) and providers (i.e., clinicians) to the medical makers (i.e., HCI researchers). This collaboration allows these stakeholders to pool their expertise, creating a shared foundation of knowledge concerning hand edema treatments and potential solutions using textile-based wearable technologies. Additionally, by covering both the fabrication and implementation processes of MediKnit devices, our work aims to provide insights into soft medical making approaches.

6.15 RELATED WORK

Our contribution builds on prior work on medical making, treatment regimens of edema, and digital fabrication of textiles.

6.15.1 *The State of Medical Making*

Medical making has emerged out of the increased access to fabrication technologies (e.g., 3D printing) in a wide variety of fields, such as HCI, manufacturing, and material sciences. The core idea behind medical making is to equip healthcare professionals with the tools they need to design and manufacture medical devices for their patients [128]. Medical making is brought on by the barriers presented by the fabrication process, such as the technical expertise required to use modeling software, like computer-aided design (CAD), Rhino, or 3D Max. Moreover, healthcare facilities often lack the necessary equipment for fabricating these devices. To overcome these obstacles, Hofmann et al. introduced an optimized design framework [98], which leverages domain-specific knowledge, including clinical knowledge, in operating dig-

Table 7: The clinical studies below were structured as control/experimental studies. (Abbreviations in the table are as follows: IPC: intermittent pneumatic compression, MLD: manual lymph drainage, AROM-PV: active range of motion-pulpa vola, VAS: visual analog scale, COPM: Canadian occupational performance measure, ROM: range of motion, 9HPT: nine-hole peg test, DASH: disability of the arm, shoulder and hand score, and ADL: activities of daily living.)

Reference	**Intervention**	**Measurement**	**Results**	**Duration**	**Design Tool**
Haren et al. [104]	MLD (40 mins), elevation, exercises, and compression glove (day and night)	Volumeter	Median decrease of 30 ml in the posttreatment experimental group	Over 60 days	Not available
Meyer-Marcotty et al. [152]	Cooling compression period (10 mins) before sterile of arm and cryo-cuff with 30 mmHg (3 - 10 mins)	Pain VAS, ROM, volumeter, and DASH score	No significant effect on the measurements between control and experimental groups	22 days	Not available
Roper et al. [197]	IPC, standard physiotherapy	Volumeter and Motricity Index	No statistically significant difference between the 2 groups	Two sessions of 2h a day for 4-wk treatment period	Not available
Flowers et al. [67]	A: retrograde massage, B: string wrapping, C: B with intermittent A, and D: B with continuous A	Circumferential measurement	A: 1.35%, B: 1.74%, C: 3.46%, and 2.95% (average circumferential reductions)	5 minutes	Not available
Knygsand-Roenhoej et al. [123]	Isotoner	Volumeter, AROM-PV, pain using VAS, ADLs, and COPM	The experimental group showed a greater reduction than the control group (at 9 weeks)	Up to 26 weeks	Not available
This work	MediKnit device	Volumeter, ROM, 9HPT, and Figure-of-Eight	Decrease in some measurements, but no statistical significance	90 minutes	Available

ital fabrication tools. This culminative work has contributed to a shift in digital fabrication towards a "knowledge-based" workflow, where expertise drives the design.

Despite the transition from a skill-based approach to knowledge-based digital fabrication, the outcomes of medical making are still primarily limited to 3D printable objects. These rigid devices have proven valuable for applications like assistive tools and orthotics, but they may fall short for PTs and OTs who specialize in therapies that require adaptable and compliant instruments, such as massage, taping, or chiropractic adjustments. The current medical-making paradigm does not accommodate the specific needs of these professionals. Furthermore, certain medical conditions, such as edema, exhibit varying appearances and traits depending on individuals. It can be challenging for current medical-making approaches to meet the demand for customized designs, leading to reliance on one-size-fits-all solutions. This approach diminishes effectiveness, particularly in intricate areas like finger digits, toes, and hands, where a personalized fit is essential. Lastly, the existing medical-making processes do not prioritize rapid manufacturing, which is crucial for medical conditions that require swift progress and devices for intricate anatomical sites on the extremities.

The cumulative effects of these limitations in current medical-making frameworks highlight the need for design tools that enable the design of soft, compliant devices customized for individuals, reducing turnaround times. These tools empower healthcare professionals to enhance patient care and cater to individuals with diverse and rapidly evolving medical conditions.

6.15.2 *Treatment Regimens of Hand Edema*

The presence of swelling in the hand, as previously discussed in Section 6.14, presents unique challenges distinguishable from edema in other parts of the extremities. Given that the hand is situated at the most distal end of the body's lymphatic system, managing edematous fluid involves delicate stimulation of the hand.

The literature recommends various primary treatments, including elevation, active movements, retrograde massage, and compression [13]. Elevation therapy, a passive treatment, involves placing the edematous hand above the heart to leverage gravity for fluid drainage. While effective when combined with other treatments, elevation alone yields negligible effects [154]. Active movements play a role in enabling muscles to contract and pump out edematous fluid. However, conditions such as muscle spasticity accompanied by edema can limit hand movement [143]. Compression, a widely used treatment, can be delivered passively or through active therapies. Passive compression employs specialized gloves with tight fabric structures to apply force to the hand. Active compression therapy for the hand differs from therapies for arms or legs, which employ intermittent pneumatic compression. Active compression therapy for hands requires tools like strings, short-stretch bandages, or kinesiotapes attached to finger digits, the palmar area, and the dorsal sides of the hand [13]. Strings wrapped around the hand displace fluid proximally, but caution must be exercised to avoid damaging the lymphatic system with excessive pressure. Short-stretch bandages and kinesiotapes are utilized to lift the skin, reducing pain and stimulating lymphatic vessels to facilitate fluid drainage.

Moreover, the literature highlights retrograde massage, namely manual edema massage (MEM), as a highly effective therapy [13, 154]. Therapists or patients themselves conduct massages from distal to proximal sites in the hand, promoting upstream fluid drainage. It is stressed that minimal traction should be applied to prevent the collapse of lymphatic vessels. In conclusion, it is suggested that hand edema demands a more delicate and fine-tuned therapeutic approach, a goal that this work aims to achieve.

6.15.3 *Digital Fabrication for Textiles*

The emergence of digital fabrication has resulted in remarkable design and material adaptations, offering opportunities for the HCI community to create products towards customized and personalized ends. Within this paradigm, textile fabrication has experienced a significant evolution wherein more accessible tools allowed a broader scope of adaptations in knitting [6, 7, 95, 136, 171, 208, 221, 261, 271], weaving [10, 214], sewing [131], and felting [180]. These technological advancements play a crucial role in facilitating the creation of textiles that are not only tailored to individual preferences and needs but also functional applications.

Among various textile fabrication methods, machine knitting has become prominent for its capacity to create lightweight, breathable, flexible, stretchable, and conforming structures. Its capability to create soft and highly customizable structures has given rise to the development of complex geometries [105, 186] and knit interfaces, including flexible sensors [4, 250, 251, 271], actuation [8, 9, 119], haptic and tactile sensation [7, 118, 140], shape-changing interfaces [9, 139], and robotic textiles [119, 139]. It supports a diverse range of functional applications recently to include medical devices [120]. However, machine knitting presents its own set of challenges, requiring users to overcome a steep learning curve and attain expertise. To address these challenges, researchers have explored the implementation of software tools. McCann et al. [146] presented a compiler to turn high-level shape primitives such as tubes and sheets into low-level machine instructions, and Narayanan et al. [161] demonstrated a computational approach for converting mesh-based geometric input into instructions for a computer-controlled knitting machine. Further research considered integrating visual programming interfaces for creating 3D objects and doubly-curved surfaces [115, 162].

While all these design and software tools alleviate the technical complexities inherent in general knitting applications, the clinical domain requires a specialized tool that seamlessly incorporates healthcare providers' clinical knowledge, sparing them from complex knitting technicalities. The MediKnit design tool stands out by providing visualization and supporting adjustments with precision down to one pixel, without involving clinicians in the technical details of knitting. Moreover, in clinical applications, timely device delivery with minimal iterations is crucial [97], a goal actively supported by MediKnit.

6.16 MEDIKNIT SYSTEM

The MediKnit system consists of four core components: (1) the knit fabric substrate infusing passive compression, (2) active compression through shape memory alloy actuators, and (3) the hardware system that enables programmable compression parameters through a printed circuit board (PCB) (Figure 48), and (4) a design tool that integrates all components for the fabrication of the resultant device. In our current implementation aimed at fabricating a personalized rehabilitation device, our central goal is to develop an effective edema mobilization system tailored specifically for the index finger and palm. However, our vision for MediKnit goes beyond the current prototype, envisioning it as a comprehensive hand device capable of extending the proposed compression mechanism to include other fingers and the wrist.

6.16.1 *Knit Substrate*

The knit fabric fulfills three functions: (1) applying passive compression through differential elasticity of the substrate, (2) covering the area of interest, and (3) forming "channels" to integrate actuators. The knit substrates are fabricated using a digital v-bed knitting machine (12 gauge SRY 123 Shima Seiki), through the Shima Seiki's Apex 3 machine knitting software (KnitPaint) [54]. We utilize a fully fashioned knitting machine to create two symmetrical panels—one for the front and the other for the back of the hand—which are subsequently seamed

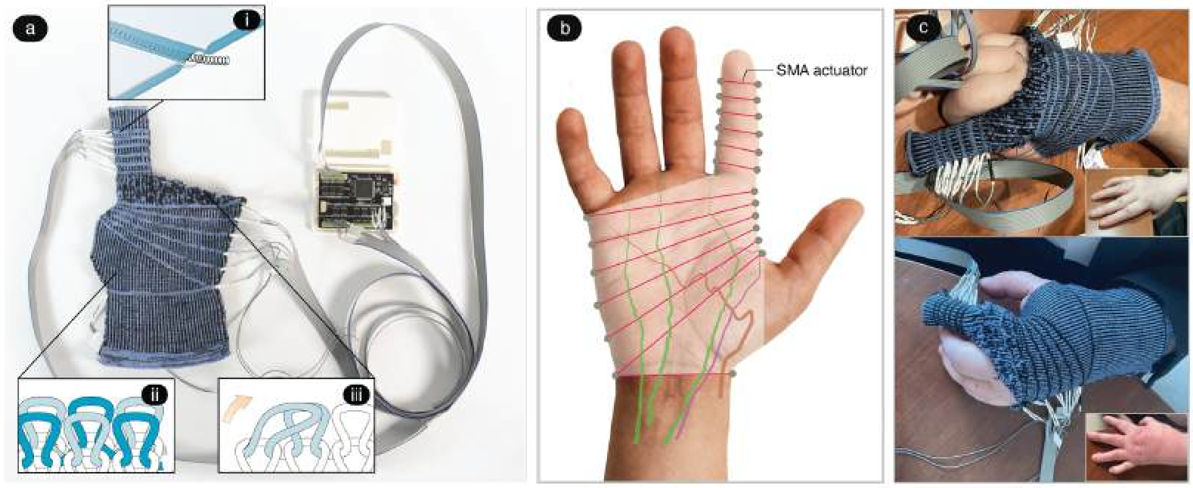

Figure 48: (a) MediKnit system consists of a knitted substrate, 13 shape memory actuators, and hardware. (i) Substrate creates "channels" for actuators, (ii) accommodates swelling in the prominent direction, and (iii) covers hand corners. (b) The 13 actuators are designed based on lymphatic vessels distribution. (c) MediKnit device on participants with hand edema. Superimposed pictures show visible compression marks.

together [233]. Each panel is imported as a bitmap file to knitting machine software to generate a full gauge interlock structure. The auto-processed panels are knitted from the cuff to the finger utilizing a double system, in which two feeders operate simultaneously. This double system creates a more balanced and durable structure than a single layer-structure. With the SRY machine, knitting the finger first would have required additional courses in the sacrificial hem area due to the minimum width of the hem required by the machine. Following knitting, the panels are seamed together to form the MediKnit device in its entirety.

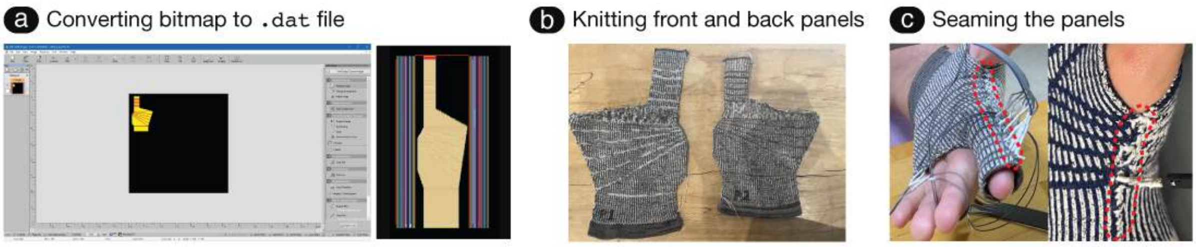

Figure 49: (a) The conversion of a bitmap file to a .dat file is performed using KnitPaint. (b) The .dat file is knitted as front and back panels. (c) The panels are seamed to form MediKnit device.

6.16.1.1 *Passive Compression*

Passive compression is a common strategy for managing hand edema and is utilized in methods like Isotoner gloves, string wrapping, taping, or Coban wrapping [154]. Prominent passive compression in the MediKnit device can be achieved by (1) adding elastic yarns to deliver higher compression, (2) creating denser knit structures, (3) shortening loop length, and (4) sizing the device tighter.

In our current implementation, we utilized Puma and Sting (elastic) yarns from Silk City, which imparted high elasticity to the substrate. Additionally, we set the loop length to 30 on the knitting machine, which creates a relatively tight structure as a shorter length of a yarn loop condenses a structure. We adopted *interlock structure* to address the swelling, offering increased stretchability across the hand's width. The interlock structure is designed to exhibit varying elasticity across the lateral and lengthwise directions. The elastic modulus along the length of the substrate was measured at 0.3 MPa, whereas on the lateral side, it was found to be 0.16 MPa. This anisotropy is considered suitable for accommodating the swollen shape of hands, where the radial volumetric increase tends to be more common than the longitudinal volume increase. Furthermore, another property of the interlock structure is its composition of a double-layer structure, rendering it thicker than other structures renowned for notable lateral elasticity. This additional thickness not only provides enhanced stability but also contributes to greater durability over time.

Consequently, the device compresses the hand even without the help of actuators.

6.16.1.2 *Seamless Fit and Free Form Channels*

We employ a *shaping* knit technique to achieve partial coverage of the device. This involves incorporating non-rectilinear shapes into the fabric panels. To incorporate actuators we adopt *tubular jacquard structure* [118]. This tubular structure generates hollow pockets that have the flexibility to expand in free forms, allowing for the creation of free-form patterns that can intersect with one another (Figure 48). Furthermore, the width of these pockets can range from the size of a single stitch (less than a millimeter) to several inches, accommodating a diverse range of actuator sizes.

6.16.2 *Active Compression*

To address the requirements of hand edema, we optimized the compression parameters for two main areas of the MediKnit device: (1) the index finger, and (2) the palm. The findings from this research will guide the development of the next version of the device, which will cover all fingers.

6.16.2.1 *Anatomical Factors for Active Compression*

Literature shows that lymph vessels in fingers originate near the fingertip's pulp, extending towards the web space, while numerous veins converge on the dorsum side of the hand [222]. Despite variations in palm lymphatic veins among individuals, all veins originate from the palm and transition towards the dorsal side of the hand before coursing towards the wrist [141]. The design of MediKnit is significantly influenced by the anatomical mapping of these lymphatic vessels in the index fingers and palm. Specifically, we apply compression to the web space between the index finger and thumb, where the veins transition from the ventral to the dorsal side of the hand. In our current implementation, MediKnit device covers the index finger and the palmar and dorsal sides of the hand (i.e., the palm and back side of the hand) up to the wrist, excluding the other fingers. This design applies cyclic pressure to facilitate fluid movement towards the upper lymphatic system. The aim of this research is to establish the foundation for achieving full hand coverage in the next iteration.

6.16.2.2 *Shape Memory Alloy Springs Actuators*

To fulfill the low-profile characteristics of the device, we used nitinol shape memory alloy (SMA) springs (Kellogg Research Labs, inner diameter: 0.5 mm, wire diameter: 0.25 mm, transition temperature: 45°C). As we Joule heat SMA springs while anchoring the tips, it generates strain up to 20% [205]. The contraction of SMA is controlled by the current. The pulse width modulation (PWM) signal, relative to the resistance of the SMA, regulates the current. Due to the varying resistance of the custom lengths of SMA, personalized actuation was necessary. We adjusted the PWM value within the range of 1 to 127. When a PWM of 80 was applied to all SMA springs, those positioned on the finger heated up to temperatures of 31.6°C while those on the palm ranged between 30.2°C and 31.6°C, respectively, resulting in subtle compression. Conversely, at a PWM of 127, the finger SMAs heated up to 40.4°C, while the palm SMAs ranged between 37.8°C and 39.8°C. When tested on a hand, this temperature range was found to be comfortably warm with pronounced pressure. We present a heat map captured with a thermal camera at different PWM values for reference (Figure 50). We make it our design principle to activate springs proximally (i.e., from the fingertip to the wrist direction), and provide a personalized level of compression by conducting a compression calibrating session during the user study before intervention.

To calculate the radial force (RF) applied by each SMA, at a PWM of 127, we measured the linear force (F = 0.39 N) and linear displacement (dx = 50 mm) for an SMA with the same length (100 mm) as that used on the index finger of a glove, fabricated for a silicon dummy finger. Next, we measured the diameter displacement (dD = 1.6 mm) of the SMA embedded in the glove and wrapped around the silicon dummy finger. Utilizing the formula $RF = \frac{2}{(\frac{dD}{dx})} \times F$, we found that the radial force from each SMA around the index finger is approximately 0.24 N.

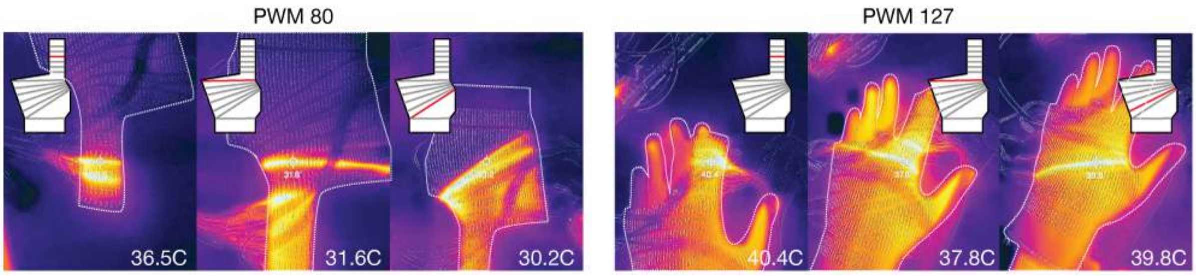

Figure 50: Left: Heat map of the actuated glove placed on a table. At a PWM of 80, SMA springs on the finger reached 31.6°C and on the palm 30.2 - 31.6°C. Right: Heat map of the actuated glove while worn on the hand. At a PWM of 127, finger temperatures hit 40.4°C and palm temperatures 37.8 - 39.8°C, creating a comfortably warm sensation with pronounced pressure. While SMA springs are actuated sequentially, it takes time for recently activated SMAs to return to room temperature.

6.16.2.3 *The Index Finger*

For the index finger, we reconducted the compression test from the literature [120] as we shared identical specs of shape memory alloy springs and knit substrate structure, and verified that the results were replicable. We followed the reported number of compression bands of six and the duration of compression of thirty seconds in the study.

6.16.2.4 *The Palm*

Determining the compression parameters for the palm was particularly critical, as it presents a distinct set of challenges compared to the fingers as laid out in Section 6.16.2.1. The complex network of lymphatic veins in the palm area shows that the veins reverse their courses through the thumb's web space toward the dorsal side of the palm. Our goal was to (1) distinguish the site of interest that our device covers, (2) optimize the division of the palm site accounting for the mapping of lymphatic vessels, and (3) ensure minimal reverse flow of fluid back to the distal direction. Before parametrizing the palm area, we established that the area of interest was from the metacarpophalangeal (MCP) pads (knuckles) down to the wrist crease (device coverage as indicated in Figure 51). Given the device design, which excludes coverage of the thumb and the rest of the fingers, we divided possible coverage of the palm into an area that covers the circumference of the thenar muscle ($\overline{a_1c_1a_nc_n}$ in Figure 51), and the other that covers the circumference of trapezoidal space between the thumb web space and the outer edge of the palm ($\overline{a_1b_1a_nb_n}$ in Figure 51). This design considers the natural distribution of lymphatic vessels in the palm and aims to provide targeted support.

To determine the number of compression bands (n_{band}), the width of each channel and the minimum distance between the channels are calculated. Considering that $\overline{a_1a_n} \geq \max(\overline{b_1b_n}, \overline{c_1c_n})$, we used the following condition:

$$(n_{band} - 1) \times d_{gap} + (n_{band} \times d_{channel}) \leq \min(\overline{b_1b_n}, \overline{c_1c_n})$$

Where d_{gap} represents the distance between compression bands, and $d_{channel}$ is the width of each channel. Using average measurements from individuals (4 without edema and 5 with edema), we calculated that $\overline{b_1b_n} \approx 28$ mm and $\overline{c_1c_n} \approx 38$ mm. We set d_{gap} to 3 mm and empirically determined that $d_{channel}$ of 2 mm provided optimal SMA enclosure. Using these values, we deduced that the maximum integer that satisfies $n_{band} = 6$. This parametrization of a hand, utilized in the backend algorithms of the MediKnit design tool (Figure 53), enables the design tool to provide a visual representation of the device and generate precise coordinates for the placement of SMA channels. Detailed explanations and illustrations regarding this process are available in the supplementary document.

6.16.2.5 *In-Vitro Palm Compression Characterization*

Given the scarcity of established systems for simulating fluid mobilization, we explored mock circulatory loop (MCL) systems, typically used for testing cardiac assist devices [32]. We

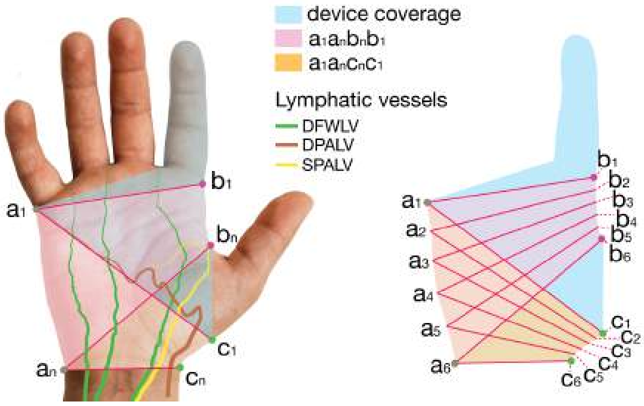

Figure 51: The figure on the left is adapted with permission [141]. Deep finger web lymph vessels (DFWLV) run from the palmer side of the hand and turn their courses to the dorsum side of the hand. These vessels run short after crossing the web spaces. Similarly, one or two of the superficial palmar arch lymph vessels (SPALV) also flip their courses as they run past the web space between the index finger and thumb. In contrast to the other vessel groups, deep palmar arch lymph vessels (DPALV) run horizontally toward the thumb, penetrating the adductor pollicis (i.e., the thick muscle attached to the palmar side of the thumb). With $\overline{a_1 b_1 b_n a_n}$ and $\overline{a_1 c_1 c_n a_n}$, we ensure the coverage of these lymphatic vessel groups.

also incorporated a silicone mock hand due to its elastic properties, which closely mimic human skin [61]. While MCL systems mimic aspects of the cardiovascular system, our focus was on the return of interstitial fluid through the lymphatic system. After consulting with rehabilitation physicians, we developed a mock hydraulic system (Figure 52). This system applies external pressure to a compressible silicone hand saturated with water, facilitating fluid drainage through a resistance mechanism. It allows observation of fluid backflow, aiding our understanding of fluid displacement trends.

To conduct our experiments, we created a mock five-finger hand consisting of a silicone encapsulating sponge saturated with water, attached with an outlet on the wrist (see Figure 52 (b)). The six compression bands divide the two areas. Our objective was to empirically identify the amount of fluid displaced by each band when under the same voltage, measured by the amount of water coming from the outlet. We randomized the order of the 12 compression bands, and measured the water displacement while applying current to each band for 30 seconds. We repeated a randomized order three times to account for the degradation of SMA and tested four different order sets. The results reported the descending order of pairs as in Table 8. Considering shorting issues, we eliminated crossing bands to avoid shorting and selected the six most effective bands. For instance, as we select $\overline{a_3 b_3}$, we eliminated the bands

Table 8: Averaged displacement of water of 12 SMA bands. The most effective band was ranked as 1.

Band	Displacement	Rank	Band	Displacement	Rank	Band	Displacement	Rank
$\overline{a_3b_3}$	0.06%	1	$\overline{a_5b_5}$	0.02%	5	$\overline{a_2c_2}$	0.01%	9
$\overline{a_6c_6}$	0.05%	2	$\overline{a_4c_4}$	0.02%	6	$\overline{a_4b_4}$	0.01%	10
$\overline{a_6b_6}$	0.04%	3	$\overline{a_2b_2}$	0.01%	7	$\overline{a_5c_5}$	0.00%	11
$\overline{a_3c_3}$	0.03%	4	$\overline{a_1b_1}$	0.01%	8	$\overline{a_1c_1}$	0.00%	12

that cross it, namely $\overline{a_ic_j}$ ($i < 3$, $j < 3$). Following this method, we finalized 7 bands: $\overline{a_1b_1}$, $\overline{a_2b_2}$, $\overline{a_3b_3}$, $\overline{a_4b_4}$, $\overline{a_5b_5}$, $\overline{a_6b_6}$, and $\overline{a_6c_6}$.

Figure 52: (a) Experimental setup to observe backflow displacement of fluid from the fingers to the hand. The sponges utilized exhibited uniform porosity. The image on the right shows no discernible displacement of pigment from the onset (left). (b) Setup to characterize compression bands in the palm. The silicone mock hand was positioned flat embedded with 12 SMA compression bands.

Additionally, we qualitatively tested if there was any reverse flow of water back to the distal sites of the hand through the translation of pigment. This investigation is crucial to ensure that the pressure applied to the palm does not inadvertently result in edematous fluid being drawn back to the distal part of the body. Similar to the prior experimental setup, we prepared a silicone hand and filled the fingers with sponges saturated with plain colorless water, while filling the palm area with a sponge saturated with pigmented water (Figure 52 (a)). The selected 6 compression bands were actuated under the same voltage for 30 seconds each for 8 sequences, and they were compared with the onset using video and photographs. We did not observe water migrating back to the finger.

6.16.3 *MediKnit Hardware*

We developed a rigid 44 by 61 mm printed circuit board embedded with an Atmega 2560 microcontroller. The board is powered by a 3.7V, 1200mAh LiPo battery and provides varying duty cycles programmed for each spring, allowing freedom for individual intensity of compression (Figure 48). Through pulse width modulation (PWM) the board controls 8 two-channel MOSFETs (IRF8313 TRPBF), and subsequently 13 compression bands (i.e., 6 for the index finger and 7 for the palm, from Section 6.16.2.5). The duration and intensity for every compression band can be programmed by changing the duty cycle and PWM duration. The power consumption of the board is 263mW. We used top-entry connectors to attach ribbon cables from the SMA springs to the board.

6.16.4 *MediKnit Design Tool*

The objective of our design tool is to facilitate and support clinicians in the creation of personalized hand gloves for individuals dealing with edema. The design tool enables adjustment of (1) the template of the knit glove and (2) the placement of the shape-memory alloy channels. The key features of the tool are measurement parametrization, template creation and adjustment, and channel generation and adjustment. To implement these functionalities, we employed JavaScript, Canvas API (inbuilt in JavaScript), and utilized the React library [1], creating a web-based application (Figure 53).

Our design process starts with a parameterized 2D glove template, serving as the base for clinicians to tailor the wearable to individual needs. Subsequently, users, including clinicians, fine-tune the glove template overlay while it's superimposed on the image of the patient's hand, incorporating feedback from the patient, especially if specific considerations are required. Following this, the finger and palm channels are automatically generated, and the design tool provides users with the flexibility to make individual adjustments to each channel. Finally, users can save the generated glove template for further processing and fabrication (see Figure 54).

While our design tool enables users to modify the design, it also enforces a few design constraints based on the characterization results. These constraints include the number of SMA, minimum distance between the channels, channel width, and materials used (yarns and SMA).

1 https://react.dev/

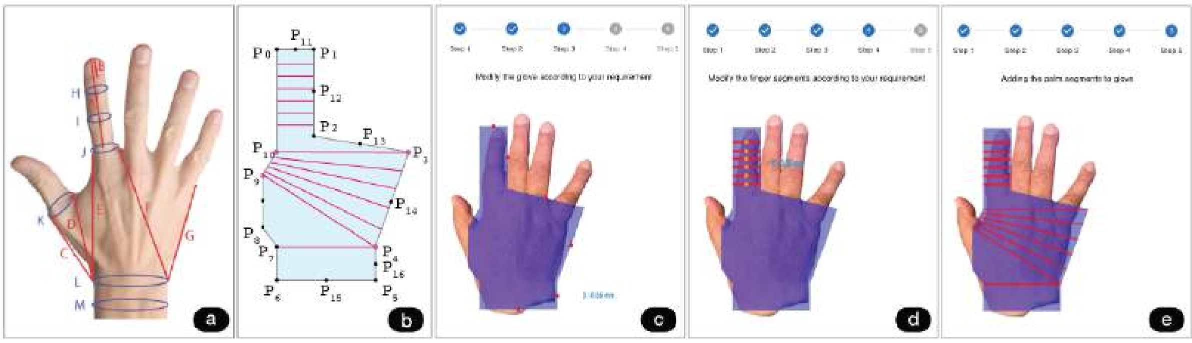

Figure 53: MediKnit design tool provides: (a) Visual guidance for thirteen hand measurements for customization; (b) Backend algorithm converts the measurements to 18 coordinate points; (c) and (d) A glove template is generated based on these coordinates, with options for therapists to adjust both the template and SMA channels; (e) The design tool then creates a machine-readable file.

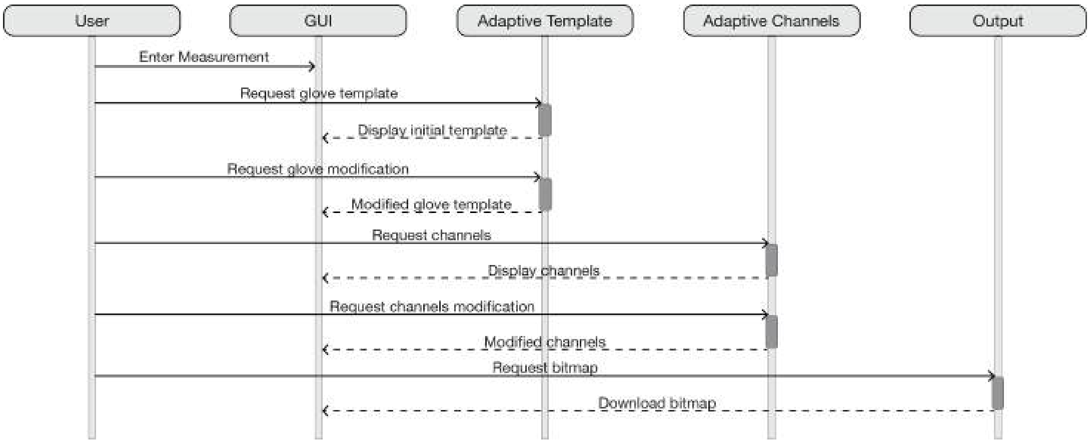

Figure 54: Sequence diagram of MediKnit design tool.

6.16.4.1 *Hand Parameterization*

In the absence of standard measurements for optimal customization of the site of interest, we defined 13 specific measurements (from A to M) to generate 18 coordinate points, from P_0 to P_{17}, that construct a reliable 2D hand model (Figure 53 (a), (b)). To facilitate this process, the design tool provides visual guidance for these measurements in the initial step, as illustrated in Figure 53a. The user is required to measure an edematous hand's dimensions using a ruler or a caliper and subsequently input these measurements into the interface. This simplified approach reduces the necessity for specialized equipment, such as a 3D scanner, simplifying the design process. In addition to the measurement values, the user is also asked to upload a photo of the patient's hand on a flat surface, which further assists in the adjustment process.

6.16.4.2 *Adaptive Template*

Next, the design tool utilizes a set of formulas (provided in our supplementary document) to convert the 13 measurements into the coordinate points, approximating the hand model and generating a geometric 2D contour. This involves simplifying the actual hand contour into rectilinear shapes, ensuring compatibility with the knitting machine and the knit structure. The design tool provides 6 controller points (see Figure 53c), enabling the user to fine-tune the length and width of the index finger, palm, and wrist within the generated glove template. To facilitate this adjustment, the user can utilize the superimposed image, make observations, and consider feedback from the patient as guides for resizing the glove. Upon achieving the desired adjustment, the user can save the design and proceed to the next step.

6.16.4.3 *Adaptive Channels*

As outlined in Section 6.16.2, the design tool generates 6 channels on the index finger and 7 channels on the palm. With those channels, the design tool provides the user the option to fine-tune the channels on the finger and palm. The user can move channels in case the patient presents specific needs or unique requirements or to avoid sensitive parts around the bony area of the hand. This adaptability ensures that the final position of channels aligns precisely with the patient's individual specifications, ensuring optimal comfort and functionality.

6.16.4.4 *Creating Knitting Machine-Readable File*

Upon completion, the user has the option to either review previous steps or, if satisfied with the template, save the design (Figure 53e). If the user opts to save the design, the system will convert it into a machine-readable bitmap file, which then can be read on Knit Paint. Additionally, users have the option of saving the modified measurement values for future reference.

6.17 MEDIKNIT DEVICE CASE STUDIES THROUGH WORKFLOWS

Aligned with our emphasis on how domain-specific knowledge drives decision-making for medical making, we garnered insights from two groups of users who possessed specific domain knowledge and expertise in clinical rehabilitation and digital machine knitting, respectively. Namely, we investigated fabricating MediKnit devices through two different workflows: (1) the **knitting technician-led workflow**, which is deemed the traditional method to design customized garments (Figure 55), and (2) the **clinician-led workflow** using MediKnit design interface (Figure 56). We obtained insights into each workflow through interviews with technicians and clinicians.

6.17.1 *Participants*

In both workflows, we recruited 6 participants experiencing hand edema from and . This paper presents case studies featuring patients from in the knitting technician-led workflow, whereas cases involving patients were reported through the clinician-led workflow. , a regional rehabilitation clinic, specializes in hand therapy and lymphedema management programs. , a medical institution with a rehabilitation outpatient clinic offering physical and occupational therapy, serves patients with diverse diagnoses, such as stroke, brain injuries, and spinal cord injuries. The participants, aged between 40 and 78, primarily undergo clinicians' manual edema mobilization (MEM) therapy. While the frequency of physical therapy sessions varied among the 6 participants, with some receiving more frequent sessions than others, the maximum frequency was limited to once a week. This project obtained IRB approval for both sites, A and B.

Table 9: Participant information. MEM: manual edema mobilization (i.e., retrograde massage); IPC: intermittent pneumatic compression device; OT: occupational therapy.

Code	Age	Gender	Standard of Care	Other Conditions	Care Site
P1	70	F	MEM, IPC, compression glove	None	CMC
P2	40	M	Home maintenance	Muscle stiffness, hypersensitivity	CMC
P3	53	F	MEM, hand therapy	None	CMC
P4	73	M	Manual massage	Muscle spasticity	WCM
P5	78	M	OT, fine motor therapy	Insensate hand	WCM
P6	65	M	Home maintenance using Bioness	Muscle spasticity	WCM

6.17.2 *Case Study 1 - Knitting Technician-Led Workflow*

The technician-led workflow positions a knitting technician as the principal designer of MediKnit. This workflow follows the typical fabrication process for wearable devices, where an engineer/technician fabricates the device without clinical input. Instead of using the MediKnit design tool, the technician employs a proprietary tool called Apex 3 from Shima Seiki as the primary fabrication medium. Our objective was to examine the fabrication procedures and design rationale employed by the technician, aiming to identify the specific priorities considered.

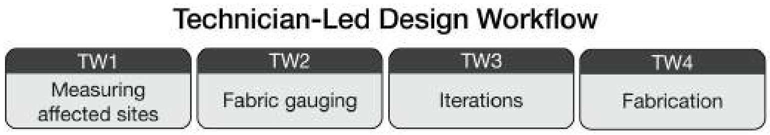

Figure 55: Technician-led design workflow.

6.17.2.1 *Knitting Technician as a Domain-Expert Participant*

In addition to the three patient participants recruited from (P1, P2, and P3, Table 9), one of the authors took part as a knitting technician. She had 3 years of experience in manual and digital knitting and was proficient in garment knitting using the Apex 3 tool. She was familiar with the actuators and structures used in the device. She had not received training in occupational or physical therapy.

6.17.2.2 *Protocols*

The protocol for this workflow comprised four steps. The devices were tailored to three patient participants recruited from (Table 9). Using the measurements obtained, the technician customized devices in a manner aligned with her typical garment manufacturing process.

TW1: Hand Measurements for Customization. This workflow aimed to acquire the measurements necessary for customizing devices. The three patients (Table 9) recruited from participated in a survey, providing details on basic demographics, their standard of care, frequency of therapy, and 13 anthropometric measurements of the hand (Figure 53 (a)).

TW2: Fabric Gauging. In this workflow, the knitting technician set the gauge for the yarn and structure employed to ensure uniform dimensions in the device. This process entailed iteratively knitting samples and subsequently blocking them; a method involving soaking the swatch and allowing it to dry without wringing. The fabric's gauge was measured once within this workflow and maintained consistently throughout the customization process.

TW3: Iterative Knitting. Subsequently, the technician created panels drawing on her own garment knitting expertise. She engaged in an iterative process of knitting panels and measuring their dimensions to ensure alignment with the collected measurements. The design constraints identified once within this workflow and remained consistent across both workflows, encompassing factors such as width and the number of channels, adhering to established guidelines for generating channels on the palm side.

TW4: Device Fabrication. Once the technician completed the design, she exported it to machine-knittable files and transferred it to the knitting machine. After the device was knitted, the panels were seamed, and the actuators were integrated and wired to the PCB.

6.17.2.3 *Analysis*

The pre-survey from TW1 (Section 6.17.2.2) was digitally distributed to patients and completed remotely by the participants. To maintain a comprehensive record of the fabrication process, the technician logged daily work progress. The researchers later analyzed this written record and photographs for insights and observations.

6.17.2.4 *Knitting Technician as a Medical Decision Maker*

In manufacturing devices, the technician followed a conventional garment-making process. The knitting technician designed devices on Apex 3 software and knitted them with the same setting as the other workflow. Due to the specific nature of the jacquard structure, the technician chose not to utilize the automatic garment process feature on KnitPaint but to design the devices manually from scratch. It is worth noting that, as one of the study conductors, the technician actively observed the implementation of the devices in the study, providing comprehensive insights. In the following summary, we detail the customization process for each patient based on her design log and observations.

- **P1.** In the fabrication process of P1's device, the technician assumed a non-swollen forearm and wrist, designing the cuffs to match the tightness of the hand, following a typical garment-making process. This tightness led to P1 adjusting her arm position and manipulating the cuffs during the study. Consequently, the SMA was exposed, which would typically be within the insulated area. This exposure resulted in a brief short-circuiting of one channel. Although P1 reported discomfort due to the heat, she insisted on continuing the study after identifying the issue's cause. The technician later acknowledged that she should have taken note of P1's primary care response, which was a pneumatic compression sleeve. The technician recognized that this information could have provided a hint that the swelling might extend to the rest of the arm.
- **P2.** The fabrication process for P2 started before P1, but it suffered a relatively prolonged delay, necessitating additional iterations due to the absence of a "baseline design" for reference. Consequently, the technician completed the device several weeks beyond the expected implementation date. Upon delivery of the device for the user study, it became apparent that P1's swelling had intensified, resulting in the device being uncomfortably tight. Additionally, P2 expressed specific discomfort related to his sensitive index finger. The technician recalled strictly adhering to the measurements, which led to the over-compression of the index finger for P2, who experienced heightened hypersensitive tactile senses due to inflammation in the finger. The initial device was returned, and study conductors re-measured P2's hand. The technician adjusted the design based on the new measurement, incorporating extra room in the index sleeve to minimize tightness. The final version of the device did not exhibit issues during the user study.
- **P3.** Drawing from the outcomes and insights gleaned from the preceding processes, the technician attentively reviewed the survey responses, discerning potential considerations beyond mere measurements. In the case of P3, who did not exhibit any specific conditions, the technician adhered to the established "baseline" design schema without introducing

additional looseness to the device. The implemented device carried out compression successfully.

6.17.2.5 *Results*

In this segment, we report insights stemming from our case study centered around individual patient experiences.

- **Need for Holistic Knowledge.** What P1's adverse event (P1 in Section 6.17.2.4) signals is the importance of considering and accounting for the full extent of a patient's condition and care when designing and fabricating the device. In the case of P1, the reliance on a measurement-based design assumption, without considering the potential impact of swelling beyond the hand, led to issues during the study. The lesson underscores the need for a more individualized and holistic approach, tailoring device design to the specific conditions and characteristics of each patient. It highlights the significance of thorough communication with patients regarding their care and any potential implications for the device.
- **Prone to Multiple Trials and Errors.** The delay in the fabrication process for P1, stemming from the absence of a "perfectly fitting" baseline design, highlights how iterative trials caused prolonged turnarounds. Moreover, the oversight in considering factors beyond measurements, such as P1's hypersensitive tactile senses and inflammation, not only emphasizes the need for a more holistic understanding of the user's unique conditions but also potentially hinders the timely delivery of the device. The abrupt changes in the swelling of P2 underscore the importance of delivering the device within a swift timeframe.

6.17.3 *Case Study 2 - Clinician-Led Workflow*

The clinician-designed fabrication workflow positions clinicians as key decision-makers in developing MediKnit. Using MediKnit's design tool, these healthcare professionals were able to contribute to the clinical decision-making process actively, ensuring precise fitting and addressing the comprehensive clinical needs of each patient.

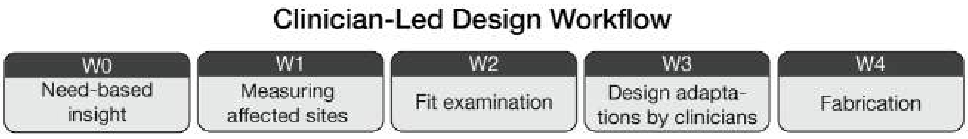

Figure 56: Clinician-led design workflow.

6.17.3.1 *Clinicians as Domain-Expert Participants*

In addition to the patients, we invited 9 clinicians from site B to create devices for the patients using the design tool. All clinician participants were female, with backgrounds ranging from average experience (less than 20 treatments, 1 participant) to extensive experience (more than 21 treatments, 8 participants) in working with patients with hand edema (Table 10).

Table 10: Information of clinicians participated in this workflow.

Code	Age	Gender	Experience (yr)	Care Site	Code	Age	Gender	Experience (yr)	Care Site
C1	35	F	12	Site B	C6	38	F	21	Site B
C2	40	F	25	Site B	C7	41	F	6	Site B
C3	44	F	9	Site B	C8	48	F	18	Site B
C4	42	F	13	Site B	C9	36	F	14	Site B
C5	53	F	8	Site B					

6.17.3.2 *Protocols*

The protocol for this workflow consisted of five steps (Figure 56). Initially, we conducted a survey to gather insights on needs from clinical domain experts (W0). Next, patient hand measurements were taken, measuring identical 13 anthropometrics of the hand (W1), and a passive device was created using MediKnit's design tool. Participants then took part in a fit examination session to put on the fabricated device (W2). Subsequently, clinicians utilized the design interface to customize the template's size and adjust the compression band size and position (W3). Finally, a functional device was fabricated with the support of a technician (W4).

W0: Gathering Need-Based Insights. To better understand the variation of hand edema and the necessity for customized devices, identify the requirements for developing a design tool, determine suitable features to assist clinicians in the customization process, and gain insight into when to integrate the design tool within the clinician-led design workflow for optimal outcomes, we invited 9 clinicians (Table 10) from to participate in a survey. They were given 10 minutes to answer 4 questions (Table 11). All technical terms were explained before the survey started. The survey aimed to gather insights into the variance of edema across patients based on their experiences (Table 11, Q1), the requirements for a digital tool to aid their design process (Table 11, Q2), specific features that would assist them if included in a design interface (Table 11, Q3), and their preferences between optimized and customized design suggestions (Table 11, Q4). This information contributed to the development of the design interface discussed in Section 6.16.4. Subsequently, the completed questionnaires were collected to extract insights.

W1: Hand Measurements for Customization. The next step began with the collection of patients' hand measurements. We recruited 3 patient participants (P4, P5, and P6) from site B and requested their physical attendance at the measurement session. We recruited one staff member from to measure patients' hands. During this session, a photo of the patient's hand with edema was taken on a flat surface and saved as a reference to be used in the design interface.

W2: Device Fit Examination Session. The measurement data, along with a photo of the participant's hand, was uploaded to the design tool to generate a 2D representation of the template. The design tool then produced an optimal template for MediKnit's device, superimposing it over the participant's hand photo. Subsequently, the design tool generated a machine-readable bitmap file based on the information gathered from TW2 and TW3. Following this, a technician helped fabricate the initial version of the glove, utilizing the generated template, without the active compression components. Next, the fabricated non-functional devices were sent to the participants to be worn and examined for how well they fit the participants' hands. During a subsequent 15-minute Zoom call, we recorded photos and videos of participants wearing the MediKnit devices, with their consent. The photos and videos were de-identified.

W3: Device Adaptations by Clinicians. To gain a comprehensive understanding of how clinical knowledge influenced the design process, occupational and physical therapists were invited to a design adaptation session. Three clinicians (C1, C2, and C3) from , all of whom had participated in the needs-finding survey, were invited. Two interviews were conducted with C1 to customize the template designs for P4 and P5, while C2 and C3 were interviewed together to customize the device for P6. Each session, conducted via Zoom, lasted 40 minutes, with clinicians providing consent for audio and video recording. During the session, photos and videos of individual participants were shared with the clinicians. Then clinicians used the MediKnit design tool and superimposed templates as guides to customize the template size and adjust the size and position of compression bands. Throughout this process, the design tool enforced fabrication constraints, such as the number of compression bands, the minimum gap between them, and the width of the compression bands. After completing the design adjustments, the design tool generated a file compatible with a knitting machine, and clinicians were instructed to save the final design for further fabrication processes. The session concluded with a semi-structured interview, during which clinicians responded to eight questions (Table 12).

W4: Device Fabrication. During this phase, the file generated by the MediKnit design tool was employed for knitting the device, with the support of the knitting technician. It is important to note that the knitting technician did not modify the designs created by clinicians, preserving the integrity of their clinical decisions. After the fabrication of the MediKnit device was completed, and the active compression components were integrated, and the device was incorporated into user studies to assess its performance with patients experiencing hand edema.

6.17.3.3 *Analysis*

The researchers collected and analyzed clinicians' responses from the need-based survey (Table 11 from W0) to extract insights. Audio recordings of the semi-structured interviews were digitally transcribed for theme identification. Two experienced researchers independently conducted iterative coding of all qualitative data. Salient themes were identified based on thematic analysis, using codes with a reasonable degree of agreement among the coders.

6.17.3.4 *Preliminary Need-Based Insights*

Insights from the need-based survey (W0) were obtained after collecting and analyzing completed questionnaires. Regarding question 1 (Table 11), clinicians noted the variance of edema, influenced by factors such as the etiology of edema (e.g., stroke), anatomy, immobility, acuteness, pain level, wounds or injuries, and pitting. These findings underscored the need for customized devices tailored to individual patient needs. Table 11 summarizes clinicians' responses to questions 2 to 4. Notably, they favored a design tool supporting realistic rendering (44.4%), multiple design options (33.3%), and real-time simulation (22.2%). Almost all clinicians (8 out of 9) preferred a tool enabling optimized and personalized designs. Regarding design changes, 55.5% favored post-fabrication modifications, while 45.5% saw value in customizing devices before and after fabrication. These insights guided us in gathering requirements for developing a design tool, prioritizing both optimization and personalization. We considered employing the design tool to fabricate the initial glove for each patient without active compression (pre-fabrication). Subsequently, clinicians can modify the device during an adaptation session using our design tool (post-fabrication modification).

6.17.3.5 *Clinicians as Medical Decision Makers*

In step four (W3), clinicians independently utilized MediKnit's design interface on their personal systems to adjust the designs without our intervention. The following summarizes outcomes from the three design adaptation sessions conducted with clinicians.

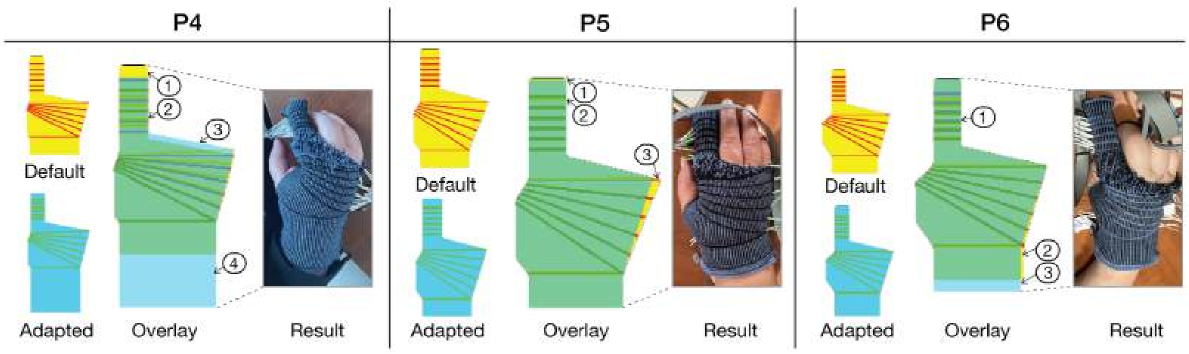

Figure 57: Visual representation of machine-readable knitting files showcasing the default design generated by the MediKnit design tool (utilized in W2, labeled in yellow) and the modified design by therapists labeled in green.

Table 11: Need-based insights.

Questions	Options	Responses
Q1: Does edema show more variability across patients than other conditions? Please elaborate (Sec 6.17.3.4)	Yes	8
	No	1
Q2: What are the essential requirements you would seek in a software used for designing medical devices?	Reduced iteration time	0
	Numerous design options	3
	Realistic rendering	4
	Optimised designs	0
	Real-time simulation	2
Q3: What feature(s) would you prioritize in a software tool designed to aid in customizing medical devices?	Design tool provides an optimized design	1
	Design tool allows personalization of design ground	0
	Combination of previous options	8
Q4: At what point would you implement design changes when modifying devices for edema patients using a software tool?	Before the device is manufactured	0
	After the device is fabricated/tried on the patient's hand	5
	Both, before and after the device is manufactured	4

- **P4.** C1 made adjustments to the default design template for P4, who faced challenges due to severe muscle spasticity and limited thumb movement. Obtaining a flat-hand photo of this participant was difficult, leading to using a hand image with a folded thumb in the design interface. C1, upon reviewing recorded survey responses and the medical history of the participant, suspected edema in all fingers and the palm. Considering the limited range of motion of the hand, C1 recommended a slightly looser fit for ease of application, emphasizing the need for personalized adjustments based on individual conditions.

  C1 underscored the importance of case-specific customization, exemplifying that severe spasticity and full-hand edema may require comprehensive coverage extending up to the middle of the arm for optimal fluid movement. While the current version of the MediKnit device does not cover the thumb, C1 suggested implementing active compression up to the base of the thumbnail in the case of an edematous thumb. C1 recommended the possibility of extending device coverage to include other fingers and addressing swollen knuckles with coverage of the finger web space. Following these considerations, C1 accessed MediKnit's design interface to implement the suggested adjustments. She extended the length of the sheath covering index finger (Figure 57, P4. 1) and metacarpophalangeal (MCP) joints (knuckles) (Figure 57, P4. 3) and then lengthened the cuff to encompass the entire wrist (Figure 57, P4. 4). Additionally, she fine-tuned the first channel on the index finger to align precisely below the nail base (Figure 57, P4. 2). C1 expressed a desire to add more channels to the device's cuffs, a feature currently unavailable in our current implementation.

> ***User Study Observation**: Due to the design adaptations to the cuff, P4 effortlessly grasped the extended cuff during the study, which facilitated device donning. Extending the cuff was essential for an optimal fit, eliminating potential difficulties. Notably, P4 reported no discomfort during the user study.*

- **P5.** In this session, C1 was tasked to customize the default design generated by our interface for P5. After reviewing the recorded photo and video from the fit examination session (W2), along with a brief patient history, C1 accessed MediKnit's design interface. Based on her observations, C1 decided to extend the index finger sheath (Figure 57, P5. 1) and enhance the device's fit on the palm by narrowing the width on the knuckles, adjusting the template closer to the pinkie finger (Figure 57, P5. 3). Drawing on kinesiology, C1 emphasized the importance of channels passing closely around joints (but avoiding them) for efficient fluid flow and accordingly adjusted the channels on the index finger (Figure 57, P5. 2). C1 concluded by underlining the significance of patient diagnosis information (e.g., what caused edema) for personalization, stressing the need to know the patient's level of active movement. Additionally, she expressed a desire to incorporate more channels on the palm, especially if the thumb has edema, a consideration for future iterations.

> ***User Study Observation:** The final device fit P5's hand successfully, causing no discomfort or overcompression.*

- **P6.** Clinicians C2 and C3 collaborated to customize the design for P6, who presented with severe muscle spasticity and a thumb curled into the hand. Based on their observations, the clinicians opted to tighten and lengthen the palm (Figure 57, P6. 2) and cuff (Figure 57, P6. 3) to enhance coverage, maintaining sufficient looseness for easy donning. They believed the length of the device on the index finger was suitable and adjusted the channels (Figure 57, P6. 1) to ensure proper positioning below the fingernail and to avoid the joints.

  User Study Observation: *Unlike P4, P6's muscle spasticity and stiffness led to lateral curling of the hand. The device, designed with a relatively short width, suited P6 well, with no reported issues of looseness or tightness.*

6.17.3.6 *Results*

Clinicians' responses to the semi-structured interview (Table 12) were analyzed and categorized into three themes, which are discussed here.

Table 12: Key inquiries in the semi-structured interview.

#	Questions	#	Questions
Q1	Have you used personalized medical devices in your practice?	Q5	What additional information would you need to fabricate MediKnit device?
Q2	Give us examples of one-size-fits-all devices and challenges faced when using them.	Q6	Assess the potential applicability of the MediKnit design tool for other medical conditions.
Q3	Do you think customized medical devices are effective?	Q7	How could clinicians aid the designing and customization of medical devices?
Q4	What do you think is the role of medical devices in treating or managing edema?	Q8	Are there technical/knowledge barriers preventing clinicians from fabricating medical devices?

- **Needs for Clinician-Led Design Process.** Throughout their responses, clinicians consistently emphasized the imperative of a clinician-led design process. C2 highlighted the clinician's crucial role in considering factors such as the underlying cause of edema, the level of spasticity, and the flexibility of joints during the design process. Furthermore, C3 stressed the importance of incorporating cognitive and social aspects into device design to ensure safe usage and optimize outcomes, stating, *"clinicians take into consideration the cognitive and social aspect of the patient to see what their follow-through would be. Can they actually use* *the device safely?"* Illustrating the social and motivational aspect, C2 highlighted the significance of patient motivation, stating, *"I think the patient motivation plays a part. I think a device in isolation by itself is not really going to do."* Patient conditions, particularly in cases like stroke-edema, were identified as crucial for the success of home-based device use, with C2 noting that, *"a lot of stroke patients have sensory deficits... So we tend not always to put devices on those patients."* Additionally, C1 advocated for collaborative efforts between engineers and clinicians in the design process to produce more effective prototypes, emphasizing that clinicians offer nuanced insights beyond the expertise of engineers.

- **Limitation of Existing Medical Devices.** Clinicians highlighted critical limitations in the current design and fabrication of medical devices, including splints and pneumatic devices. Current options, often limited in sizing (e.g., small, medium, and large) or relying on one-size-fits-all configurations, lack the flexibility to address specific patient needs. C1 noted that *"prefabricated splints do not allow adjustability,"* cautioning against the potential harm from "one size fits all devices" that aren't properly fitted on the patient. C3 echoed these concerns, stating that *"prefabricated devices don't always fit."* Clinicians stressed the significance of fine-tuning devices for patient comfort and clinical effectiveness, especially in cases of spasticity or varying hand swelling. Additionally, clinicians highlighted time constraints in a clinical setting, emphasizing the importance of a more efficient and adaptable solution, such as designed templates, to streamline the customization process, reduce preparation time, and enhance overall patient care.

- **Holistic Customization Beyond the Device.** Clinicians provided valuable insights into the customization of medical devices, emphasizing the importance of understanding patients' active movement and the specific conditions influencing their requirements.

  The clinicians stressed the need for comprehensive follow-up, recognizing that improvements observed during sessions might not always translate to sustained results. Information about patients' diagnoses and spasticity levels was deemed crucial for designing effective devices. Additionally, clinicians emphasized understanding patients' ability to follow instructions and receive assistance from caregivers. C1 highlighted, *"for patients with limited movement and without a caregiver, I will make the device a little looser to make it easier to put* *on."* Addressing spasticity alongside edema requires a highly personalized approach, considering the limited movement of these individuals. C1 highlighted managing edema with spasticity, suggesting lengthening cuffs for improved fluid flow and advocating against off-the-shelf devices for those with dual challenges.

6.17.4 *Takeaways From the Two Workflows*

We observed distinct differences between workflows. Clinicians viewed customization comprehensively, considering the entire process of donning and doffing the device. The technician, however, focused on achieving a precise fit to the body, ensuring no loose fabric. In terms of production time, technicians followed a traditional garment-making process with multiple iterations for precise fabric dimensions. In contrast, clinicians used a streamlined design tool, reducing the need for multiple iterations. This finding aligned with Hofmann et al.'s conclusion that occupational therapists prefer making design adjustments during client appointments rather than through iterative processes [97]. Finally, clinicians incorporated medical insights into the design of MediKnit devices, adapting for joint sensitivities and anticipated swelling, contrasting with the technician who strictly followed established design guidelines. This study highlights the differing priorities and methodologies of clinicians and technicians in medical device design.

Table 13: Reflections from the clinician-led and technician-led workflows.

Keyword	Clinician-Led Workflow	Technician-Led Workflow
Customization	Including donning and doffing	Anthopometric fit
Turnaround	Around 5 days	Around 2 weeks
Anatomical factors	Considering bony prominences	Following design guidelines
Site of interest	Extension to arm	Focused on hand

6.18 MEDIKNIT DEVICE USER STUDY

Besides the emphasis on the fabrication workflow, another goal of our research lay in (1) evaluating MediKnit's functional performance, (2) subjectively understanding the sensory perception and safety of the device on patients who may present various levels of sensory deficits, and (3) envisioning the potential of incorporation of MediKnit into daily lives. We obtained quantitative data through several measurements and surveys, and qualitative data through semi-structured interviews.

6.18.1 *Participants*

We recruited six participants retained from the earlier case study (Section 6.17.3). The participants presented edematous hands, three were enrolled from local clinic A and the other three from medical institution B. The study excluded participants with pitting-type edema, open wounds, and burn injuries, but accepted various causes including stroke, post-op, and infection. All selected participants presented swelling in one of their hands and met the eligibility criteria, with some presenting muscle spasticity and insensate fingers (Table 9).

6.18.2 *Apparatus*

As explained in Sections 6.17 and 6.18, clinicians, and a knitting technician each served as the primary maker for three MediKnit devices. All six devices were customized according to the patient's measurements, utilized the same selection of yarns, and had a single sleeve for the index finger. All devices embedded identical SMA springs sourced from Kellogg Laboratory, as described in Section 6.16.2.2.

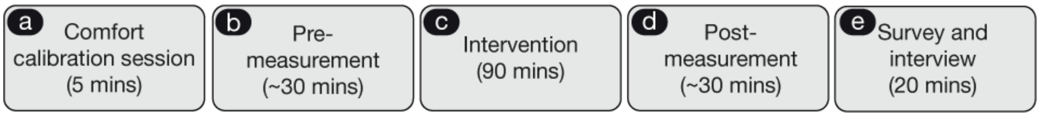

Figure 58: The flowchart of MediKnit study protocol.

6.18.3 *Study Protocol*

The user study was structured with pre-intervention measurement, intervention, post-intervention measurement, and patient interviews with surveys. Before the intervention, we conducted an initial calibration for five minutes to adjust compression and heat levels for each patient, ensuring comfort (Figure 58 (a)). Starting with minimum compression, we gradually increased it until the patient felt comfortable. Our study included methods different from the typical clinical study structure that includes control and experimental groups, focusing instead on a single intervention group. All participants wore the MediKnit device, personalized by clinicians or knitting technicians, for a 90-minute intervention (Figure 58 (c)). During this period, every 13 SMA bands (as detailed in Section 6.16.3) compressed the hand from the distal end to the wrist for 30 seconds each. To evaluate changes in swelling, we conducted four measurements on each patient before and after the intervention using different modalities (Figure 58 (b), (d)). These measurements included: (1) hand volume using a volumeter, (2) figure-of-eight measurement to assess circumference, (3) range of motion of the index finger, and (4) the 9-hole peg test (9HPT), which evaluates hand functionality. To maintain consistency; all measurements were repeated 2 times by an observer [33, 35, 134]. One researcher, who had prior experience with volumetry and ROM measurements, conducted the measurements in a randomized order, repeating each measurement twice. After the completion of the post-measurement, participants were asked to respond to a survey and undergo an interview for qualitative analysis (Figure 58 (e)).

- **Volume Measurement**: As one of the common measurements [120, 153], volumetry quantifies the volume of the affected site by submerging it into a tank filled with water and measuring the weight of water displaced from the tank. The assessment measured the volume of the whole hand, thumb, and three fingers (i.e., middle, ring, and pinky fingers). By subtracting the volumes of the last two from the hand volume, we obtained the volume specific to the palm and index finger. Custom-designed volumeters were employed to suit the unique areas of interest being measured.

- **Figure-of-Eight**: The figure-of-eight method, recommended with a tension-controlled measuring tape, involves wrapping the tape around specific points on the hand. We started at the distal ulnar styloid, extended over the anterior wrist to the distal radial styloid, and then moved diagonally across the dorsum of the hand, covering the fifth metacarpophalangeal joint line. We then proceeded from the volar aspect to the fourth metacarpophalangeal joints and, finally, moved diagonally across the dorsum back to the starting point (distal to the ulnar styloid).

- **Range of Motion (ROM)**: We assessed the flexion of the proximal interphalangeal (PIP) joint in the index finger by instructing participants to perform three movements: (1) extending the index finger, (2) flexing it to a comfortable degree, and (3) flexing it to its maximum extent. These motions were repeated two times, with each instance recorded. A computer goniometer was employed to obtain angles from the recorded videos. Specifically, we measured the internal angle of the joint formed by the distal interphalangeal (DIP), PIP, and metacarpophalangeal (MCP) joints.

- **Nine-Hole Peg Test (9HPT)**: The nine-hole peg test (9HPT) is a standardized, quantitative assessment widely recognized as the gold standard for measuring finger dexterity. The nine-hole peg test assessed (1) putting nine pegs in nine holes and (2) retrieving the pegs back to the container while using the thumb and the index finger. Participants are scored based on the time taken to complete the activities, recorded in seconds, with the stopwatch initiated from the moment the first peg is touched until the last peg hits the container.

6.18.4 *Data Analysis*

To measure the intra-rater reliability of these measurements, we conducted intra-class correlation coefficients (ICC). ICC estimates and their 95% confident intervals were calculated using R package `irr`, version 0.84.1 [258] based on consistency and a 2-way mixed-effects model.

In analyzing each measurement, we addressed the non-independence of data across participants using the linear mixed effects model using *lme4* [18]. We confirmed the normal distribution and constant variance of residuals for the measurements. We anticipated two random effects: `participant` and the interaction effect between `pre\post` and `participant`. For range of motion (ROM), we included a third random effect, the interaction among `participant`, `pre\post`, and `motions` to account for three movements.

In analyzing semi-structured interviews, we transcribed audio recordings to identify salient themes. Three experienced researchers independently conducted iterative coding on all qualitative data. We used codes showing a reasonable degree of agreement among the coders to identify salient themes based on thematic analysis.

Table 14: Intra-rater reliability of measurements and CI's lower and upper bounds. ICC score close to 1 indicates high similarity between measurements. Values less than 0.5 are indicative of poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability. (ROM: range of motion, 9HPT: nine-hole peg test, FoE: figure of eight)

	ICC [95% CI] of **baseline**	ICC [95% CI] of **post**		ICC [95% CI] of **baseline**	ICC [95% CI] of **post**
Volume	0.999 [0.851, 0.999]	1.000 [0.949, 1.000]	FoE	0.999 [0.938, 0.999]	0.998 [0.890, 0.998]
ROM	0.999 [0.996, 0.999]	1.000 [0.998, 1.000]	9HPT	0.997 [0.927, 0.997]	0.993 [0.834, 0.993]

6.18.5 *Results*

Here we report four measurements of each participant's affected hand before and after the intervention. Two patients, P4 and P6, had to withdraw from volumetry and 9HPT due to severe muscle spasticity. In this section, we report ICC scores, 95% confidence intervals for pre-measurements (baseline) and post-measurements (Table 14) for measurement reliability. We then plot descriptive data (Figure 59) and report statistical analyses.

6.18.5.1 *Measurement Results*

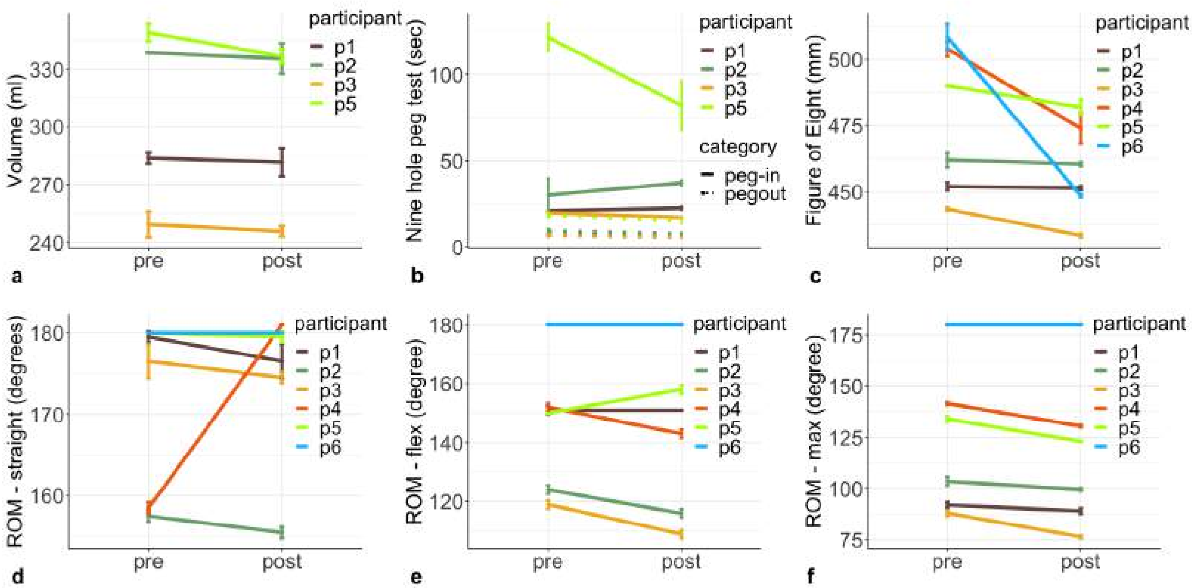

Figure 59: (a) The volumetry indicated a decrease in volume after the intervention in the descriptive data. (b) 9HPT showed a notable difference in the two activities: putting 9 pegs into the holes (trial: in) and taking them out (trial: out). (c) In the figure of eight, all participants showed a descriptive decrease after the intervention. (d),(e),(f) show ROM results; the downward slope of lines was deemed favorable, indicating a greater range of motion after intervention. P6 could barely perform due to severe muscle spasticity. (d) Patients showed a downward trend except for P4, which could potentially be attributed to overextension. (e) All patients except P5 indicated a greater ROM. (f) All patients indicated a greater ROM.

Volumetry. A decrease in the volume is deemed favorable as it indicates edema reduction. While the decrease in volume in all four patients seems negligible in absolute values, the proportional value reveals that the amount of difference ranged from 0.7% to 3.6%, which is comparable to a single 30-minute application of IPC [82]. There was a discrepancy in the sample size as muscle spasticity prevented two participants (P4 and P6) from manipulating their fingers to fit in the volumeter. In the descriptive data, all participants except the two withdrawn showed a decrease in the volume; P5, P2, P3, and P1 from the greatest to smallest difference. Statistical analysis reveals no significant changes between pre and post.

9HPT. There was, again, a discrepancy in the sample size as two participants (P4 and P6) could not perform 9HPT due to spasticity in the fingers. There was relatively high variability for P5, due to the slippage of pegs caused by compromised fine motor skills. Linear mixed effects model revealed a significant disparity in the time taken when participants were inserting and removing the pegs. However, there was no statistically significant difference between pre and post-measurements.

Figure of Eight. As with the volumeter, a decrease in the figure of eight measurements indicates a reduction in swelling. This measurement showed the least variability, as suggested by the literature [142]. In the descriptive data, all participants showed a decrease in the measurements, with P6 showing the greatest change, followed by P4, P3, P5, P2, and P1. However, our model did not indicate significant differences between the pre and post.

ROM. In range of motion, the greater the difference from the pre-measurement (i.e., downward shift of the dashed line), the more it was deemed favorable. Notable ROM differences observed in P2, P3, and P4 could be attributed to the effects of heat from SMA. Literature suggests that thermal intervention can relax soft tissue, resulting in an increase in ROM [22]. P6 could straighten his finger but could not bend it due to muscle spasticity. The mean changes in the angles for straightening, flexing, and reaching maximum flexion were 2.5°, -3.2°, and -6.8° respectively, indicating that participants were able to bend their fingers more after the intervention. The positive value for straightening indicates that patients could hyperextend their fingers after the intervention. The results from the linear mixed effects model indicated a significant difference across the three motions (p-value $< .001$). Maximum flexion, in particular, informed statistically significant difference between pre and post (p-value $< .05$). However, there were no significant changes between the pre and post-measurements in overall motions.

6.18.5.2 *Post-Study Survey and Semi-Structured Interviews.*

We obtained insights into participants' interactions with the device from the post-study survey. The survey consisted of eight questions rated on a 7-point Likert scale, focusing on wearability, tactile sensation of compression, and comfort (Table 15). The survey showed that Q8 obtained the highest median score. The majority of the questions, except for Q4 and Q6, leaned towards positivity. In the subsequent semi-structured interview, interviewers expanded the themes to include tactile sensation, feasibility of MediKnit, comparison of MediKnit to standard therapy, and accessibility of MediKnit. Our observations are summarized below:

Table 15: Questions and statements included in the survey. The survey encompassed three themes: device comfort, tactile sensations, and the experience between the user and the device.

Questions	Themes	Median
Q1: How comfortable was it to wear the device during the intervention?	Comfort	5.5
Q2: How comfortable did you find the process of donning and doffing the device?	Comfort	5.5
Q3: I became accustomed to having the device on my body over time.	Comfort	6
Q4: I felt that the device compressed all sections of my fingers equally.	Sensations	3
Q5: I had to change my arm posture or fidget while wearing the device.	Sensations	6
Q6: I found the device to be appealing to wear.	User experience	3
Q7: I felt awkward wearing the device.	User experience	6
Q8: I could see myself wearing the device in everyday life.	User experience	6.5

- **Attributes of Fabric.** Participants without muscle stiffness found donning easy and found the fabric stretchable: *"Yes, it was very easy to get on"* (P3), even allowing them to make a fist (P3), and breathable: *"I think it's a little more breathable (compared to rubber)."* (P3). Participants unanimously rejected the idea of envisioning MediKnit in latex or silicone rubber due to concerns about sweatiness and discomfort: *"It (latex) will get all sweaty."* (P1) *"Fabric is more comfortable than rubber."* (P4), *"Latex can be thinner but would be a little clammy and sweaty."* (P5). Some suspected latex will pose difficulty putting on, particularly for individuals with muscle stiffness in their hands *"It would be difficult putting it (latex) on my hand."* (P6)

- **Comparison of MediKnit to Standard Therapy.** A comparison of MediKnit to standard therapy revealed a preference among participants for the programmability of compression, as opposed to traditional methods. Some expressed a desire to customize compression settings based on personal preferences, *"so it goes up and down and with higher frequency"* (P5), while others favored a clinician-driven, prescriptive approach *"whichever one (compression setting) works better, that's what I want."* (P4). Criticisms of the current standard of edema care included a lack of personalized attention and a focus on machines: *"You go into the clinic, and they put you on a machine or something. There's no one-on-one stretching."* and *"They don't focus on you. I want something one-on-one."* (P4).

- **MediKnit as a Potential Edema Device.** The potential of MediKnit as a reliable treatment tool was discussed, with participants highlighting the portability of MediKnit as advantageous, particularly those who faced challenges with clinic commutes: *"If this thing you have here (device) is there whenever I feel like needing it, I'd appreciate that"* (P6), *"I would love the fact that I didn't have to come here"* (P3). Some participants expressed a preference for using the device alone at home: *"I would rather be alone and wear this"* (P4).

  Participants also suggested removing wires and improving the interface of the PCB: *"Wireless would be ideal, honestly"* (P3).

6.19 DISCUSSION, LIMITATIONS, AND FUTURE WORK

While our work introduces a new medium, fabric, to empower clinicians in the medical making process, potential advancements are needed to transfer domain knowledge and extend applications seamlessly.

Extending MediKnit's Capabilities and Practical Implementation. Clinicians have recognized the potential of the MediKnit design tool to customize devices for various medical applications. To extend MediKnit's application, incorporating detailed patient information, such as photographs or radiographs, will be essential. A key objective in the near term is to enhance the tool's design capabilities beyond the index finger, extending to other fingers. This enhancement will allow the flexibility to add, remove, or reposition channels on the fingers, palms, and cuffs according to individual needs. Additionally, we are developing comprehensive guides to help users apply the device correctly, ensuring optimal functionality and improved patient comfort.

To effectively implement the MediKnit system across the entire fabrication workflow and the deployment of the devices, considerable coordination among multiple stakeholders was necessary, including managing user study logistics and patient recruitment. However, once a shared knowledge base about the device's functionality was established, the required skill sets for stakeholders, such as clinicians and HCI researchers, did not exceed those typically demanded by their regular occupations. Clinicians integrated the device into their treatment regimens, while HCI researchers focused on fabricating and assessing the device based on the clinicians' designs.

Safety and Durability Concerns. The current version of MediKnit is designed for short-term use in clinical settings as recommended by clinicians, rather than for extended, continuous wear. Future iterations will focus on improving the device's comfort over longer periods. The MediKnit are made from synthetic, non-allergenic yarn using standard knitting techniques similar to those used for regular garments. This results in a knit substrate that offers breathability, stretchability, and comfort, akin to other knit garments but susceptible to wear and tear. The active compression elements, such as SMAs, may degrade over time, necessitating further research to determine their durability and the device's washability for long-term use. During intervention sessions, no issues with sweating or discomfort were observed. Contrarily, patients reported that the knit substrate of the device provided greater comfort compared to other treatments they had tried previously, such as Isotoner gloves.

In terms of safety, all wires and active compression components were carefully insulated. The electronic components and gloves underwent thorough examinations before each session to ensure they were in optimal condition. The research team, consisting of two authors, closely monitored the device throughout the intervention to maintain safety and functionality. An initial calibration was performed at the start of the 90-minute intervention to adjust compression and heat levels to each patient's comfort, starting with minimal compression and gradually increasing it as needed. Looking ahead, we plan to develop a closed-loop system that includes over-current and surface temperature monitoring to enhance device safety, especially for non-clinical uses.

Personalization Through Enhanced Tactile Feedback. Patient variability not only included hand shapes but also tactile sensitivity. Tactile perception and reaction time variations were observed during the intervention. Our findings also revealed diverse tactile sensations experienced by participants, ranging from subtle tingling to localized compression, highlighting the need to customize the device's tactile feedback to meet individual patient needs for enhanced user experience. To address this, future research will integrate tactile sensitivity measurements [**Touch-perceptions-2014**] to fine-tune the device's compression levels and distribution to better align with individual patient needs and preferences. Additionally, integrating sensory feedback can help us identify areas where the device may be causing discomfort. Ultimately, this iterative process of incorporating tactile sensitivity measurements will enable us to refine the device's design and functionality, improving therapeutic outcomes for patients with hand edema.

Enhancing Knitting Strategy through Insights from Garment Design Experts. To gain insights into our current fabrication approach, we sought expertise beyond knitting technicians and engaged with a professional garment designer. While our current approach aligns with common fabrication practices in garment design, the designer identified specific challenges related to yarn tension in the transition area between the finger and palm. Pinpointing a racking problem as the cause, she recommended adopting a simpler knit structure in this region to enhance the finish of the MediKnit device. Additionally, she suggested incorporating a more elastic structure in the joints to improve flexibility and accommodate hand movements effectively. These valuable insights provided by the garment designer are being considered for future iterations of the device. In addition, we will plan to engage more apparel/garment designers and especially seek out those with glove design expertise for continued insight to improve the knit and garment construction strategy.

6.20 DESIGN RECOMMENDATIONS

An Alternative to a Prescriptive Model. The MediKnit approach adopts a partial "prescriptive approach [97]", where the providers (i.e., clinicians) drove design choices but left compression intensity to be determined by the recipients (i.e., patients). This methodology aligns with commercial edema devices for home treatment, enabling patients to adjust treatment levels to their preference. We recommend further exploration of this patient-driven approach, particularly for medical devices incorporating actuation or stimulation features.

Centralized Fabrication for Enhanced Accessibility. While adhering to the core principle of making medical fabrication tools more accessible to clinicians, the MediKnit system distinguishes itself by adopting a centralized fabrication approach, where facilities are shared among users. This strategy proves especially advantageous for medical device production involving materials unsuitable for 3D printing, as decentralized fabrication can pose logistical challenges in such cases. By centralizing fabrication resources, we not only facilitate access to specialized equipment but also streamline the production process, potentially reducing costs and minimizing environmental impact associated with individualized production setups. Thus, we advocate for further exploration of shared fabrication facilities as a means to enhance accessibility, efficiency, and sustainability in medical device fabrication.

Leveraging Diverse Expertise for Soft Medical Making. The MediKnit demonstrates a collaborative approach that synthesizes insights from diverse domains including HCI, rehabilitation medicine, and digital knitting. By establishing a shared knowledge base, each field contributed valuable perspectives to address constraints and identify feasible outcomes. HCI researchers provided valuable insights into the functionality of actuation and electrical components, supplemented by practical implementation of the device. Knitting technicians introduced innovative digital knitting techniques, enhancing the fabrication process. Clinicians offered invaluable insights into the treatment regimen for edema, outlining constraints, logistics, and therapy requirements. To optimize soft medical device design, we recommend fostering interdisciplinary collaboration and knowledge exchange to leverage expertise from multiple domains effectively.

6.21 CONCLUSION

Medical making has grown to afford rapid prototyping and co-design processes for personalized health tools, especially in the light of the COVID-19 pandemic [128]. While 3D printing technologies have augmented the design agency of clinicians, the use of soft materials such as fabrics remains under-explored. Our focus on hand edema presents an opportunity for these tailored treatments. This paper details how MediKnit, a design tool for personalized hand edema devices, draws upon clinical expertise and allows a more functional workflow. Our user study indicates the effectiveness of MediKnit device and motivates us to further explore its use in a wide range of medical therapies.

The blending of clinical insight with soft material fabrication enhances the personalization of devices, broadening the set of patients who could benefit from affordable and portable solutions.

6.22 POSITIONING MEDIKNIT WITHIN THE DESIGN SPACE

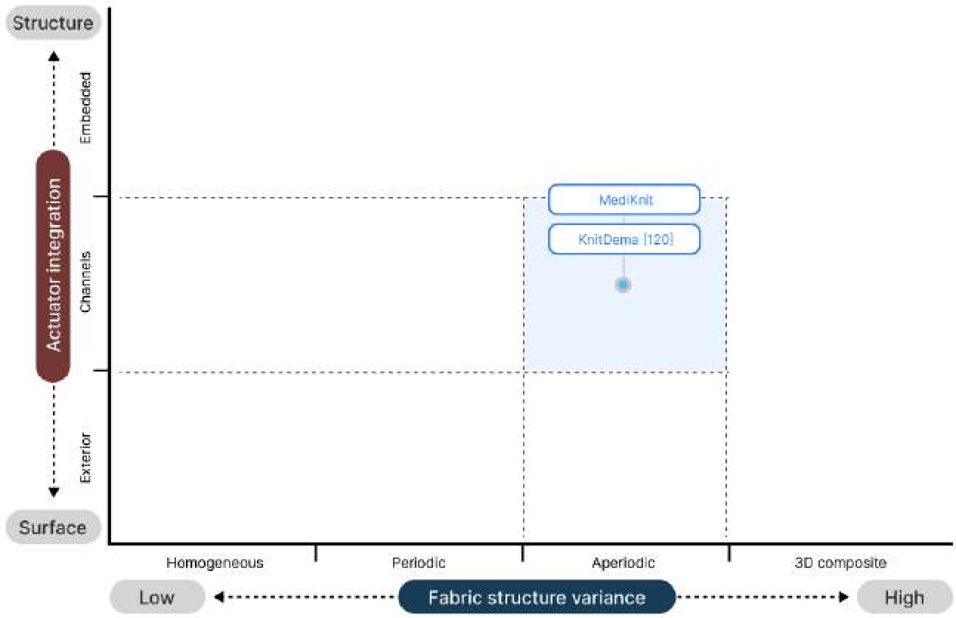

Figure 60: Situating MediKnit in the design space.

MediKnit inherits the form factor of KnitDema, situating itself within the same scales on the design parameters in the design space. Consequently, MediKnit devices are designed with *aperiodic* structures to achieve customized forms, with actuators integrated into *fabric channels* (Figure 60).

7

DISCUSSION

This thesis is motivated by the observation that current research on robotic textiles is predominantly confined to lab settings, where they are assessed in controlled and structured environments. Despite the potential of robotic textiles as wearable devices with slim profiles and improved body conformity, there have been limited approaches to making them more suited for performing tasks on the human body and demonstrating specific wearable applications.

This thesis seeks to bridge this gap by exploring how digital knitting can contribute to the design of fabric substrates that can enclose various functional components, be infused with desired properties, and be formed into shapes that conform to the human body. By leveraging digital knitting techniques, this work aims to create more versatile and practical robotic textiles, enhancing their functionality and usability in real-world scenarios. The goal is to move beyond the lab and bring these advanced textiles into everyday use, where they can perform tasks directly on the human body with greater efficiency and comfort.

7.1 REFLECTION ON THE DESIGN SPACE

At the outset of this thesis, a design space was defined to examine how fabric substrates are fabricated and actuators are integrated. The contribution of this work includes developing this design space and positioning each project within it. Each project presented a distinct wearable application, and to facilitate the application, it explored various scales within *fabric substrate* and *actuator* parameters. The performance of these devices as wearables was then evaluated in each chapter, through user studies, case studies, or characterization.

7.2 ANALYSIS THROUGH THE DESIGN SPACE

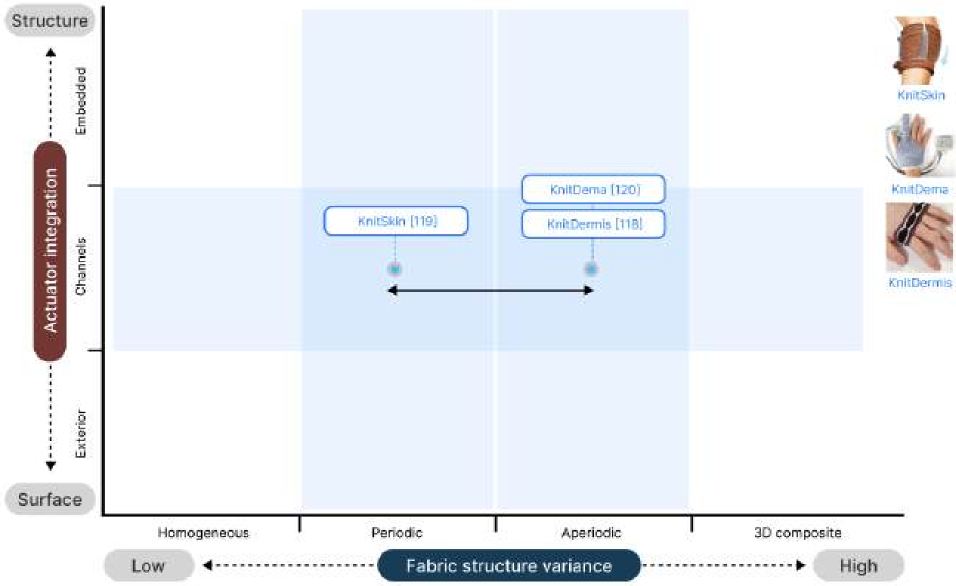

Figure 61: Revisiting the design space.

Throughout this thesis, projects consistently employed *fabric channels* as the primary method for integrating actuators. This technique was identified as the optimal method for enabling locomotion, providing tactile feedback, and applying compression to the body. As a result, my work is situated in the middle row of the design space (Figure 61).

These devices were fabricated by varying the microstructures in digitally knitted textiles, employing both periodic and aperiodic patterns, shifting along the *fabric structure variance* axis. The structural variation in the knitting process allowed for creating non-planar geometries and the customization of properties to suit specific needs. KnitSkin, for instance, demonstrated a periodic pattern in its structure to create a snake scale-mimicking substrate, which was crucial for creating frictional anisotropy that the device utilized for locomotion. On the other hand, aperiodic structural variations across the plane in projects like KnitDema and KnitDermis altered the geometry of the devices. Notably, to achieve a self-standing convex projective structure, as seen in KnitDermis, a higher variance across the plane of the knit matrix was deemed essential.

7.3 SYNTHESIS THROUGH THE DESIGN SPACE

Rather than merely analyzing existing creations, the design space can act as a catalyst for synthesis, particularly in fostering the development of novel subsets of robotic textiles. This section looks at how the design space can be strategically employed as a creative tool to conceptualize and fabricate a new group of wearable, task-specific robotic textiles. By leveraging the design space for both analysis and synthesis, we can generate pioneering solutions that combine functionality with wearability, pushing the boundaries of what robotic textiles can achieve.

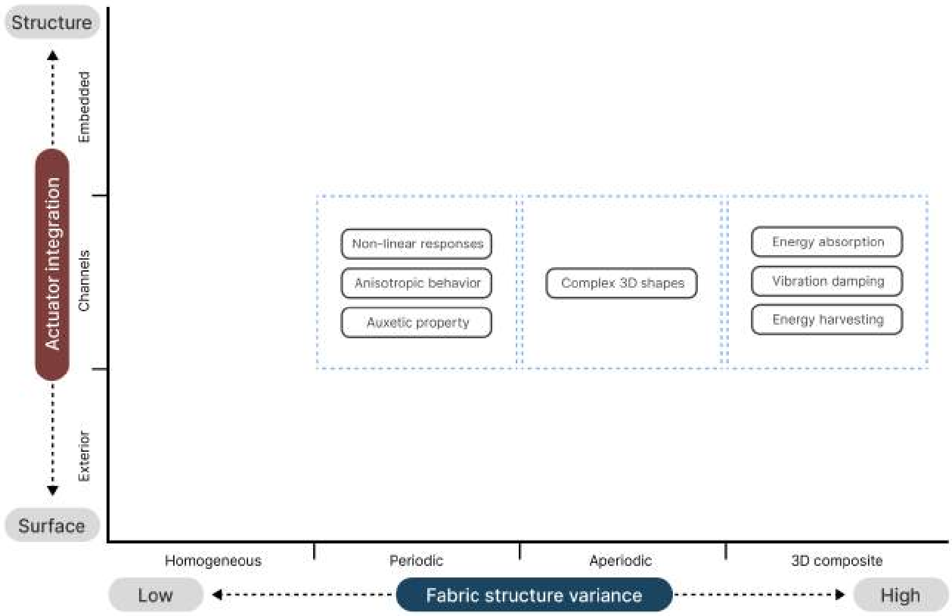

Figure 62: Robotic textiles could benefit from further exploration of structural variation to expand their application space.

7.3.1 *Enhancing Fabric Substrate Parameter*

My work has explored knit structures with periodicity and those without it, demonstrating how these structural variations result in specific properties and body-conforming shapes.

In the future, one can further engineer the periodicity in knits to achieve a broader range of emergent properties, such as auxetic behavior, and non-linear and anisotropic characteristics. These advancements could open up new possibilities for designing materials with user-defined mechanical and physical properties. Similarly, by continuing to explore aperiodic structures in knitting, one can produce even more complex shapes (Figure 62).

What's more exciting is the potential of moving toward 3D structures. I envision textile designs that combine actuation with other functions, such as energy harvesting, vibration damping, or energy absorption. These multifunctional textiles could be highly beneficial for applications in protective equipment or impact-resistant structures, offering enhanced performance and safety (Figure 62).

7.3.2 *Advancing Actuators Beyond "Integration"*

In the field of robotic textiles, actuators play a pivotal role as the primary means for deforming the textile and applying forces to the human body, thereby driving the functional performance of these devices. A deeper exploration into innovative materials is necessary to enhance the actuator integration parameter and further enrich the design space. For example, investigating materials that can be coated or deposited directly onto a fabric substrate offers a promising avenue. This approach could potentially eliminate the need for fabric channels, leading to transformative changes in the geometry parameter of the textile. Such advancements would simplify the manufacturing process and allow for more dynamic and flexible design possibilities, expanding the capabilities and applications of robotic textiles.

Alternatively, further research into the development of yarns or smart materials that can be seamlessly integrated into the knitting process and are durable enough to withstand the stresses of fabrication could significantly enhance the structural aspects of the *actuator integration* parameter. Exploring the potential of such materials, which can be freely knitted using standard machines, offers intriguing possibilities. With detailed programmability, these advanced materials could enable the design of sophisticated actuation mechanisms. This would not only simplify the integration process but also amplify the efficiency and effectiveness of the actuators within robotic textiles, opening up new avenues for innovation in wearable technology.

7.3.3 *Democratizing Robotic Textile Fabrication*

It's important to note that the designers of these textile-based devices have traditionally been engineers with expertise in the mechanics of actuators and textile manufacturing systems. As this thesis explores the utilization of robotic textiles in close proximity to the body, the future development of these textiles would greatly benefit from the involvement of designers and experts with a deeper understanding of human physiology, such as clinicians, neuroscientists, or biomedical engineers.

However, engaging a broader group of designers has been challenging due to the exclusivity of proprietary digital knitting tools, such as Shima's APEX, and the limited availability of shared knitting machines. Due to financial constraints and spatial limitations, it is often unrealistic for institutions outside of specialized research environments to acquire digital knitting machines (the cheapest industrial-grade knitting machines cost approximately 4,500 USD). Two significant changes need to occur to make this technology more accessible and to encourage collaboration from experts in various fields.

Additionally, there is a need for more intuitive and user-friendly design tools that allow designers to adapt and innovate without requiring extensive training in digital programming for knitting. Making the design process more accessible would lower the entry barrier for professionals from diverse backgrounds, enabling them to contribute their unique perspectives and expertise.

Moreover, the establishment of a shared resource pool would be beneficial. This would involve creating a system where those who own digital knitting machines can lend them out to others who need them but do not have direct access. Such a community-driven approach would democratize access to essential technology and foster a collaborative environment conducive to innovation across disciplines.

8

CONCLUSION AND FUTURE WORK

This thesis explores the construction of robotic textiles using digital knitting as the primary fabrication method. The projects presented throughout the chapters leverage the programmability of digital knitting to create knitted devices embedded with actuators. These devices conform to and adapt to the unstructured contours of the human body while generating motion when worn. This requires compliance from both the substrate and the actuators, ensuring that the devices can naturally conform to the body. Traditional wearable devices, with their stiff components, lack this flexibility and adaptability, making this approach with robotic textiles uniquely advantageous. By utilizing the inherent flexibility of knitted structures and the large deformation made possible by soft actuators integrated within, robotic textiles open up new possibilities for creating devices that are performant in various tasks. These tasks include rendering tactile feedback (Chapter 4), moving from one point on the body to another (Chapter 5), and sequentially compressing the body to cause physiological changes (Section 6.1).

This thesis aims to advance the field of wearable robotic textiles by presenting diverse methods for fabricating textile-based devices with actuation functionality within a constructed design space. This design space recognizes the complexity of wearability, understanding that no single form factor is appropriate for all applications. To address this, the thesis introduced two primary parameters that guided the development of wearable devices, ensuring they meet the varied demands of functionality, comfort, and adaptability. As a result, various form factors created by digital knitting were investigated in each chapter to ensure that these devices conform to the body effectively while carrying out tasks. For instance, some designs featured fabric pieces shaped to naturally fit the body, maintaining their form without stretching. Others were specifically tailored to elongate to fit a body part, utilizing their inherent elasticity. The chapters demonstrated that these conformal devices effectively provided various applications, including tactile feedback, locomotion across the body, and targeted peristaltic compression as intended. Each project assessed the resulting devices through material characterization, performance assessment, or mixed methods user study combining statistical analyses and qualitative interviews.

Finally, a case study was presented to offer a broader perspective on scaling robotic textiles to a wider audience. The MediKnit project (Section 6.12), developed subsequent to the Knit-Dema project (Section 6.1), investigated how an accessible fabrication pipeline could engage clinicians who had no prior experience in digital knitting. The study demonstrated that a more intuitive design tool could help overcome the high financial and technical barriers associated with digital knitting. By simplifying the design process, this tool enabled clinicians to employ various designs of robotic textiles, regardless of their backgrounds. This approach not only democratizes the creation of robotic textiles but also fosters innovation by allowing professionals from diverse fields to contribute to and benefit from these advanced technologies.

8.1 Opportunities for Future Work

8.1.1 *Advanced Design Tools for Just-In-Time Robotic Textiles*

Echoing the motivation of the MediKnit project, I envision that as the use cases of robotic textiles become more specific and cater to particular applications, engineering knowledge alone may not always provide the adequate design for these advanced textiles. Instead, professionals such as oncologists, surgeons, or firefighters may possess the necessary expertise to tailor the function of robotic textiles to their specific use cases. As demonstrated by the case study, for these groups to effectively employ their domain-specific knowledge in designing robotic textiles, there needs to be a more intuitive design tool. This tool should replace pixel-by-pixel programming with a more intuitive and visual medium, making the design process accessible to non-engineers.

Beyond the accessibility, there is potential for design tools that can automate the design process based on the wearer's comprehensive information—not just their body geometry but also their preferences, medical history, physical characteristics, genetic predispositions, and much more. Such tools would significantly accelerate the design process for non-textile engineers, reducing the time and material waste associated with manual design adjustments. By leveraging these automated systems, designers could quickly create customized, just-in-time devices that better meet the specific needs of their target users.

8.1.2 *Broadening the Functionality and Application of Robotic Textiles*

This thesis primarily focuses on the role of actuators and their integration with textiles. However, future work could explore the properties of components beyond actuation. Variable stiffness, for example, is crucial for the sophisticated manipulation of fabric substrates by adjusting compliance. Such properties should be reversible, ensuring they do not impede the fabric's compliance and ability to deform in sync with body movements. Variable stiffness robotic textiles could be useful for serving applications that can focus more on the body's protection, damping/sock absorbent features, and further lending themselves to orthoses. In such cases, the device would benefit from the breathable qualities of the fabric while remaining rigid enough to immobilize injured body parts.

Additionally, incorporating electrochemical sensing to detect the user's physiological state could significantly enhance the functionality of robotic textiles, transforming them into intelligent devices. There is a growing interest in turning fibers into bio-sensing [278] and drug-release devices [155], which could amplify the seamless integration of these components into knitted substrates without relying on conventional rigid sensors. For instance, robotic textiles equipped with bio-sensing fibers could monitor certain patient biomarkers. If a surge in the target biomarker is detected, fibers loaded with medication or hormones could immediately release the necessary treatment or embedded actuators could initiate mechanotherapy. This capability would enable timely interventions, potentially preventing medical emergencies and reducing the need for patients with compromised mobility to visit clinics frequently. This seamless integration of sensing and drug-delivery functions within wearable textiles could revolutionize patient care by providing continuous, automated monitoring and treatment.

8.1.3 *Scaling Robotic Textiles Through Shared System for Knitting Infrastructure*

As demonstrated in the KnitDema and MediKnit projects, the primary hindrances to the current fabrication of robotic textiles can be attributed to the limitations of the design tools and the lack of a shared system for knitting machines. Digital knitting machines and their programming software are often proprietary and prohibitively expensive, which limits accessibility and widespread adoption. In addition to addressing the current challenges in the design process (Section 8.1.1), implementing a shared system around digital knitting machines, similar to the sharing economy model, could significantly broaden access to the fabrication of robotic textiles. By creating a communal network where knitting machines can be rented or shared, research institutions and designers who lack the resources to purchase their own machines can still participate in and contribute to the advancement of robotic textiles. This approach could scale the development and application of robotic textiles across a broader network, fostering innovation and collaboration within the field.

Finally, while digital pipelines such as Knitout [107] have been developed among high-level design tools to lower the barrier for users, there remains the challenge that different knitting machines (e.g., SWG, SRY) require different backends to output files ready to be knitted on the specific machine. It is hoped that collective efforts will compile a set of libraries to support various machine models in the future.

While I conclude this thesis by highlighting some directions and open-ended opportunities, it is important to recognize that there are numerous other lines of research that can significantly benefit the deployment of robotic textiles in broader contexts. Beyond merely advancing the technical capabilities of robotic textiles and the infrastructure around knitting machines, there are several other pivotal concepts and approaches that can propel this field forward for the betterment of society.

Firstly, interdisciplinary collaborations could lead to innovative applications of robotic textiles. By integrating knowledge from fields such as materials science, human-computer interaction, and wearable technology, we can develop more versatile and user-friendly robotic textiles.

Additionally, exploring sustainable practices in the production and lifecycle management of robotic textiles can contribute to the environmental and economic aspects of this field. By focusing on eco-friendly materials and recycling processes, we can minimize the ecological footprint of these advanced textiles.

In conclusion, while enhancing the technical aspects that directly dominate robotic textiles' performance or their fabrication process is essential, it is equally important to consider these broader concepts and strategies to ensure the field evolves in a holistic and socially beneficial manner.

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DECLARATION

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree.

Heather Kim

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