KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting

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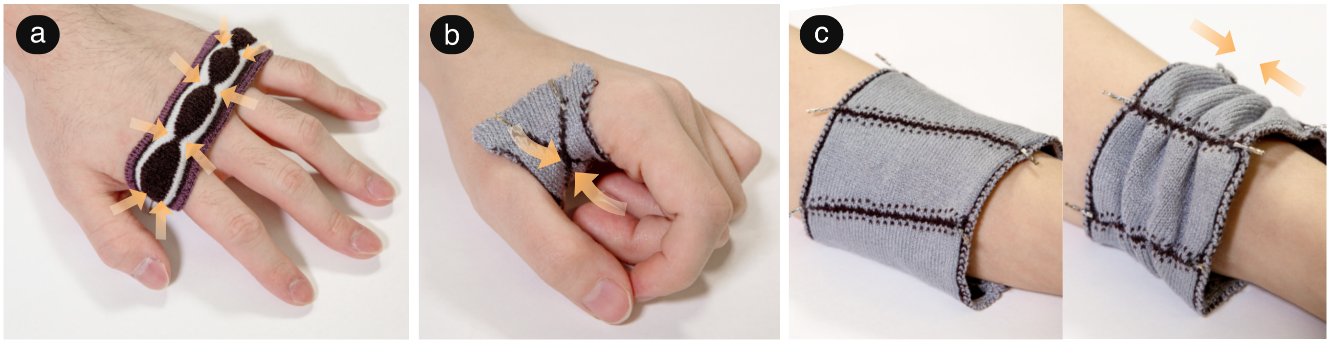

Figure 1: KnitDermis on-body interfaces deliver expressive tactile feedback on the wearer's body. Fabricated through machine knitting, they embed shape-memory alloy micro-springs in knitted channels, which deliver tactile sensations on the skin when activated. KnitDermis interfaces take advantage of the shaping properties of machine knitting for slim, stretchable, and versatile forms that conform to underexplored body locations, such as (a) protruded joints and (b) convex (hollow) body locations, delivering sensations from (a) compression, (b) pinching, (c) brushing, to twisting. We introduce knitting as a *soft* approach for crafting expressive and personal tactile interfaces.

ABSTRACT

We present KnitDermis, on-body interfaces that deliver expressive non-vibrating mechanotactile feedback on the wearer's body. Fabricated through machine knitting, they embed shape-memory alloy micro-springs in knitted channels, which deliver tactile sensations on the skin when activated. KnitDermis interfaces take advantage of machine knitting's shaping properties which allow it to generate slim, stretchable, and versatile forms that can conform to underexplored body locations, such as protruded joints and convex body locations. We introduce a fabrication approach and a series of case studies to design a wide range of form factors, textures, and tactile patterns, including compression, pinching, brushing, and twisting. We conduct a user study to elicit KnitDermis' effectiveness and wearability on diverse body locations and engage users to unpack envisioned use cases and perceptions towards the interfaces. We draw insights from our extensive research-through-design investigations on the potential of knitting as a *soft* approach for close-body and expressive tactile interfaces.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**.

KEYWORDS

Haptics, Tactile Feedback, Shape Memory Alloy, Machine Knitting, On-Body Interface

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1 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 [17, 29, 98]. 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 [22, 29, 31]), which may not be wearable and can constrain the use of the devices to certain body locations [22, 46]. 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 [105], 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.

2 RELATED WORK

2.1 Dynamic and Knitted Soft Interfaces

Dynamic shape-changing textiles have been explored for expression [8, 10, 28, 44, 87], protective heat insulation [88], medical and therapeutic purposes [18, 24], donning assistance [49, 54], compression garments [24], input sensing [82], robotic applications [11, 101, 102], and interactive architecture [14, 15]. These interfaces have integrated active shape-changing materials [8–10, 14, 15, 18, 24, 24, 58, 79, 82, 87, 94, 101], passive responsive materials [34, 74, 75], mechanical or structural mechanisms [2, 37, 48, 66], and phase-changing actuation [73]. The interfaces have been made through sewing [9, 11, 15, 44, 49, 54, 58, 82, 101], felting [8], weaving [10, 79], and knitting [2, 24, 25, 28, 34, 75, 88, 94].

Knitting has been uniquely favored not only for shape-changing effects but also for sensing and protection [81] 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* [4, 53, 63, 65, 69, 92]. For instance, Ou *et al.* [63] presented a machine-knit resistance-changing elastic stretch sensor. Despite insufficient accuracy in reading, Wijesiriwardana *et al.* [92] developed knitted resistive transducers, as well as wearable electrodes and solenoids. Paradiso *et al.* [65] 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 [28], shrink to fit the user [25], generate compression [24], and balloon out in firefighting suits [88]. Alternatively, inlaying "tendons" in stuffed knit structures [2] 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 [2, 8], 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.

2.2 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.

2.2.1 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 [32, 68, 100, 104], servo-motors [12, 13, 77], or SMAs [3, 19, 26, 33, 97], sometimes in knitted fashion [25]. A study [67] 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.* [26] 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.* [32] 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.

2.2.2 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) [47]. 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.* [76] 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 [3] 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.* [55] 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.* [22] 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 [22, 100] excite mechanoreceptors by controlling how the tactor travels. Ion *et al.* [35] 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.* [100] offers multimodal tactile sensations using a hybrid tactor but its bulky housing limits its application to locations lying flat on the ground.

2.2.3 Brushing. Unlike other stimuli, light touch, such as brushing, excites different skin receptors than pressure-sensitive ones [72]. Knoop *et al.* [43] devised tactile bars to laterally move against the skin while a belt stabilizes the device. Strasnick *et al.* [78] 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.

2.3 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 [7, 42] 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 [61]. The film-based interfaces in HCI have extensively utilized skin as an input space through capacitive sensing [40, 50, 62, 90, 91]. Given the micro-scale thickness, these interfaces have utilized gold leaf [40], lamination [51], laser-patterning [90], real-time drawing using a stylus [70], screen-printing [50, 62, 91, 96], inkjet printing [60], and printed polymeric conductive ink [91, 96] which maintain minimal thickness. More recently, 3D printing onto fabric to induce passive shape-change for on-body sensing [23] has also been proposed. Sensing systems have also been explored through IMUs [39, 51] and strain sensors [50]. For visual outputs, thermochromic pigments [40, 41, 80, 89] have been favored. Kao *et al.* have presented stiffness change as an output [38]. For vibro-tactile outputs, Withana *et al.* [96] 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 [99]. 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 [3] 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 [57] 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 [24]. A woven I/O interface with SMA embedded offered haptic feedback [80] 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 [56]. 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.

3 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 [83] and Narayanan *et al.*'s excellent glossary [59].

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 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 2).

4.1 Tactile Actuation Design Factors

4.1.1 Actuation Mechanism and Design (Figure 2(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"). 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 2(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 2(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 2(a1)). On the contrary, the actuation in the opposing directions leads to wringing of the skin, resulting in a *twisting* sensation (Figure 2(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 2(a3)), and lateral contraction results in a *brushing* sensation through the "scrunching" of the substrate (Figure 2(a4)).

4.1.2 Spatial Manipulation of Active Materials for Tactile Feedback (Figure 2(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 2(b1)), free-form curves (Figure 2(b2)), or closed curves (Figure 2(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.

4.1.3 Skin Topographies (Figure 2(c)). Tactile feedback can also be customized according to the underlying skin topography or body

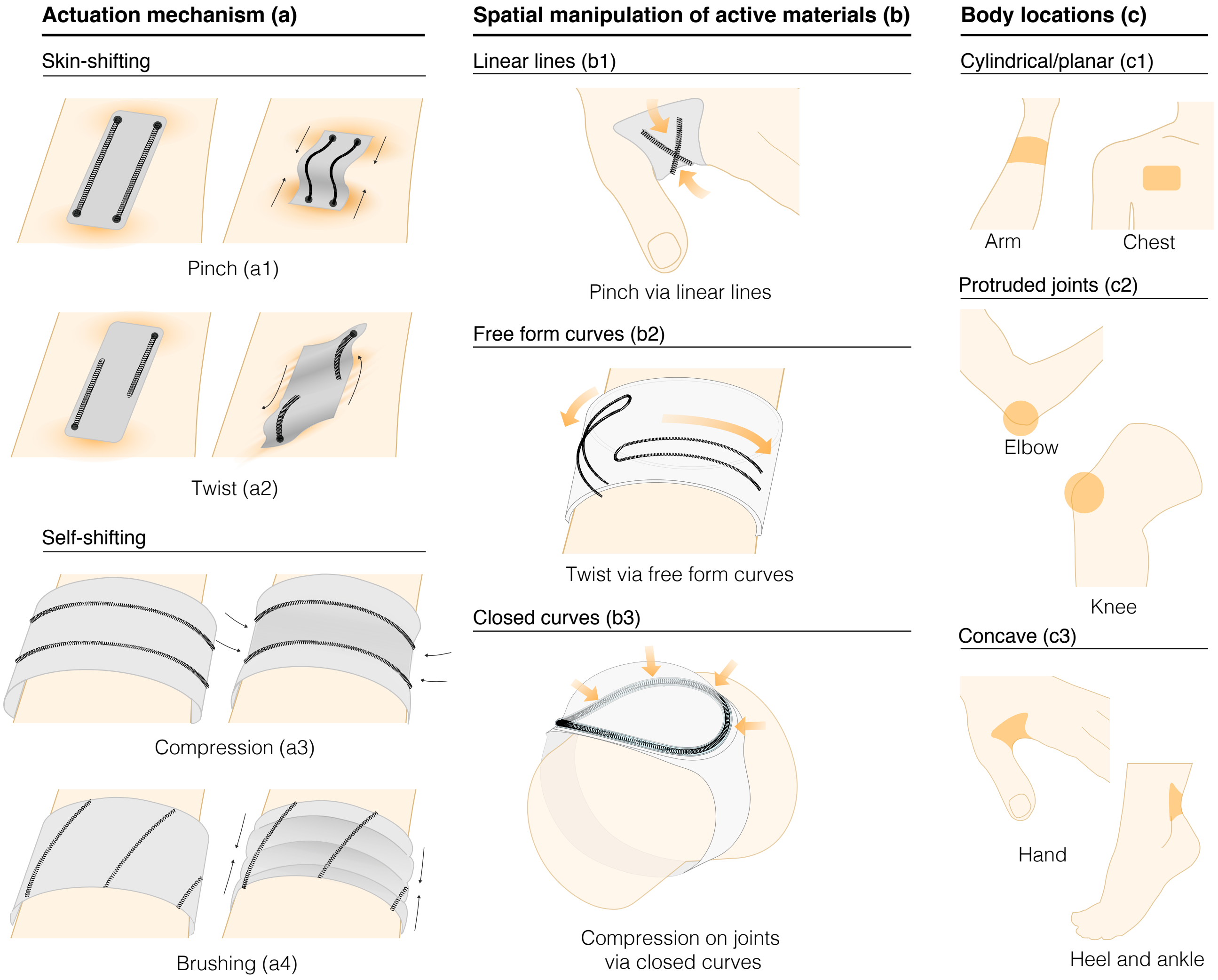


Figure 2: The main design factors for KnitDermis interfaces consist of actuation mechanism (a), spatial manipulation of SMA (b), and body location (c). Actuation is achieved either through shifting the skin in various directions (a1-2) or morphing the interface itself radially (a3) and longitudinally (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).

landmark [17, 91]. While tactile interfaces in HCI have focused placement on *planar* (e.g., back of hand) or *cylindrical* (e.g, forearm) body locations (Figure 2(c1)), KnitDermis interfaces explore challenging topographies such as *protruded body joints* (Figure 2(c2)) and *concave (hollow) body locations* (Figure 2(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.

4.2 Material Related Design Factors

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

4.2.1 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.

4.2.2 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.

4.2.3 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.

4.3 Knit Structure Design Factors

Here we elaborate on the key machine knitting structures (Figure 3(a)) we leveraged for generating KnitDermis devices, which are central to our form factor design.

*4.3.1 Knitting Free-form Integrated Channels Through **Tubular Jacquard** (Figure 3(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 3(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.

*4.3.2 Knitting for challenging body locations through **2D Shaping** (Figure 3(b)). Transfer stitches* can be used to increase (Figure 3(b1)) and decrease (Figure 3(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 3(b3)).

*4.3.3 Knitting for convex body locations through **3D Shaping** (Figure 3(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 3(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 3(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.

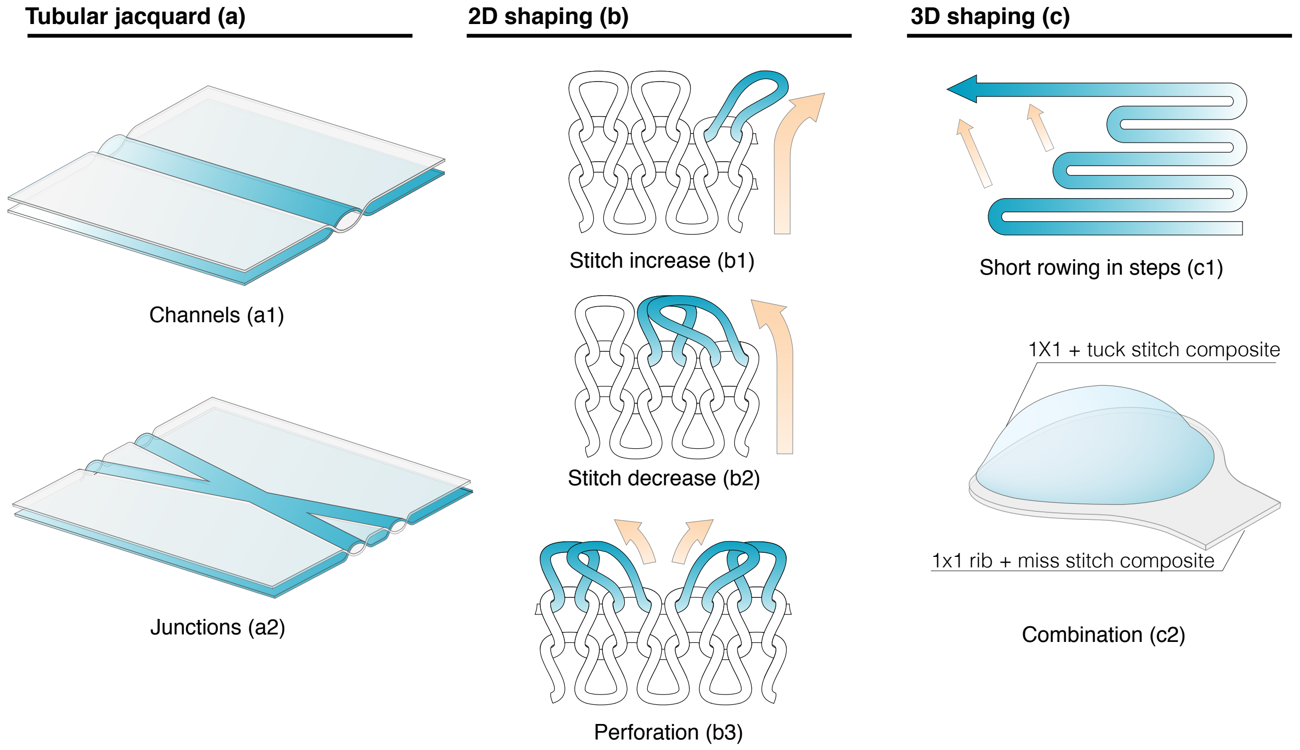


Figure 3: A catalogue of knit structures adopted by KnitDermis. Tubular jacquard (a) is used to encase active and passive materials. With complete freedom in size and shape, tubular jacquard can create channels to accommodate yarn-like materials (a1), let materials cross each other (a2) or create a pocket 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).

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.

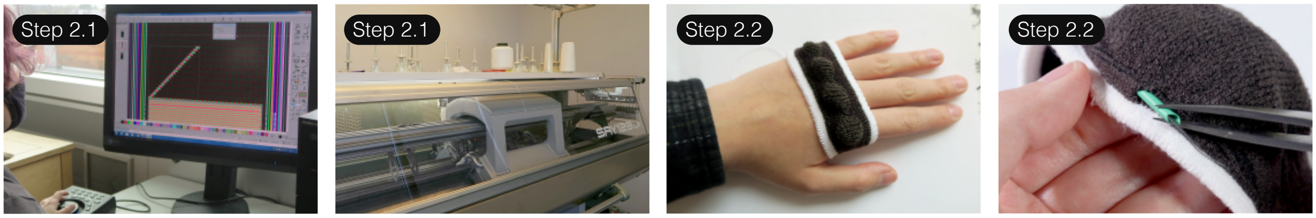
5 KNITDERMIS FABRICATION

Step 1. Sketching. We start by profiling specific body locations (according to Section 4.1.3 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 4.1.1 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.

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 3). 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 4.2.3 Non-SMA Inlay Materials.), alteration to channels can be carried out here.



Programing on Apex 3 Knitting substrates Checking conformity of SMA Threading active materials

Figure 4: 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.

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 4.3.3 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 4.1.1 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 [84]. In order to simulate twisting, the two discrete regions that move in opposite directions require a distance beyond 3.42cm (right forearm 3.28cm) [84]. 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 [45, 84]. 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.

6 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 [20, 105] 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 5 shows the implementation of eight interfaces that convey four different stimuli — compression, pinch, twist, and brushing — on the skin.

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.

Figure 5: 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 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 substructures: 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 3(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 3(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 3(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 3b). 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 [45, 84], 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 [93]. 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.

7 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* [36, 85] 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 [16].

7.1 Method

7.1.1 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).

7.1.2 *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* × *8 prototype interfaces* × *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* [36, 85] 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.

7.1.3 *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 [30, 95]. 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 [71] and *lme4* [6].

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 [86].

7.2 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?

7.2.1 *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."

7.2.2 *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

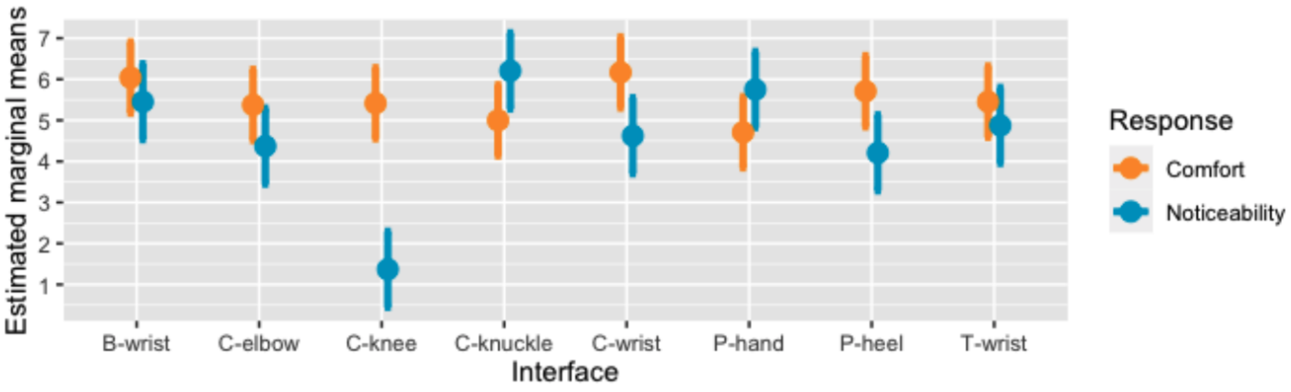


Figure 6: Estimated marginal means of interfaces, in comfort and noticeability (95% CI).

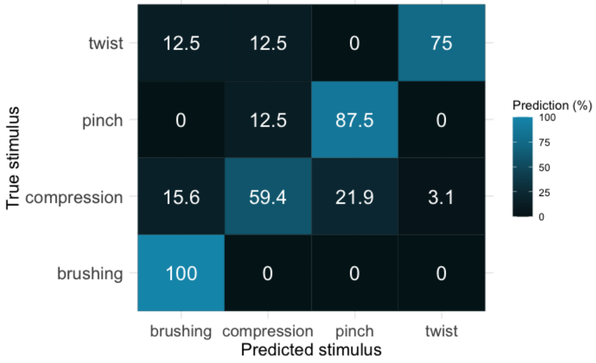
other hand, showed the highest rating at *brushing* with $M = 5.45$ ($SD = 1.47$) with the lowest rated at *compression* with $M = 4.14$ ($SD = 2.11$).

Consistent with the distinct with-in subjects tendency (Figure 6), 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?".

7.2.3 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 7). 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 8) 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.



	brushing	compression	pinch	twist
twist	12.5	12.5	0	75
pinch	0	12.5	87.5	0
compression	15.6	59.4	21.9	3.1
brushing	100	0	0	0

Figure 7: Discriminability rates by stimulus types.

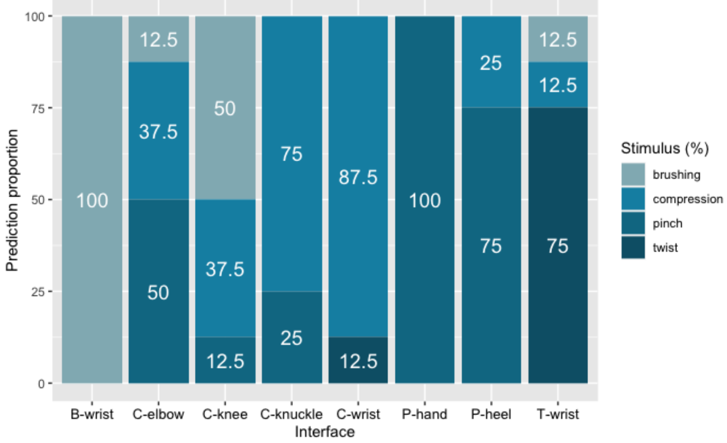


Figure 8: Discriminability rates by prototypes.

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 [1], which underscore body location as a critical factor of tactile sensitivity. Our result also extends the discussion on extra parameters in designing haptic feedback [103] by differentiating duration, contact area, and intensity of feedback.

7.3 Material Probe Phase Semi-Structured Interview Findings

We situate the KnitDermis interfaces as *material probes* [16, 36, 85] 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?

7.3.1 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."

7.3.2 Envisioned Usage and Applications of KnitDermis Interfaces.

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.

7.3.3 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

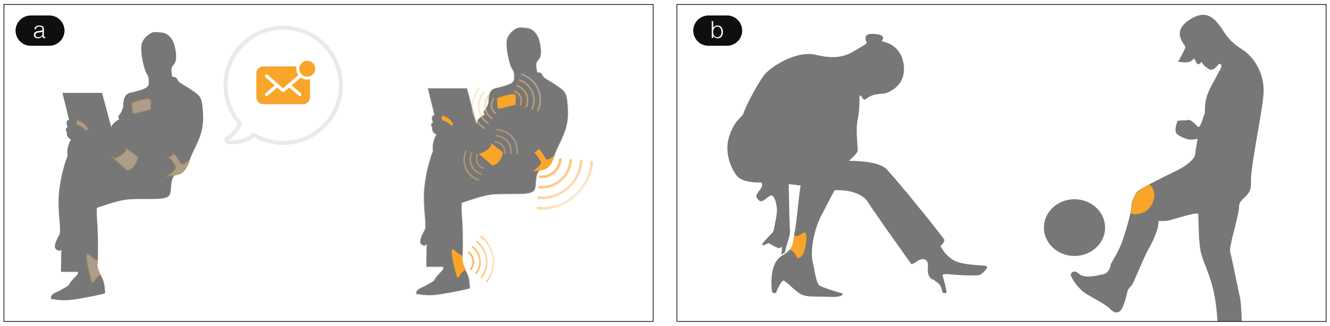


Figure 9: Envisioned use cases for KnitDermis. Participants described how KnitDermis could be worn on diverse body locations for distributed on-body notifications (a). Participants envisioned integrating KnitDermis into their everyday clothing for haptic feedback or dynamic protection (b).

the interfaces fit better when worn close to the skin. The desire for slow, gradual transitions mirror findings by Devendorf *et al.* [16], 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 [37] 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 [21] 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 [21] 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* [52] through applications such as personal communication with close ones, and therapeutic feedback for stress relief.

8 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 3(b3)) for easier threading, threading SMA springs has to be preceded by inserting soft tubes (Figure 4). 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 [27] 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 [64] at a yarn level could provide a workaround. Finally, enabling multiple heterogeneous behaviors in one micro-spring through thermal cycling [5], 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.

9 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.

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