MediKnit: Soft Medical Making for Personalized and Clinician-Designed Wearable Devices for Hand Edema

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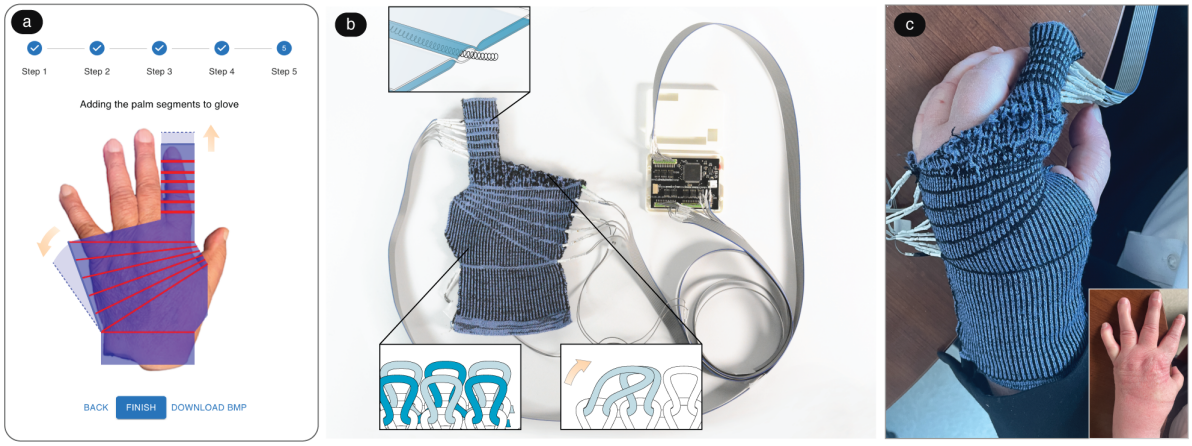

Fig. 1. *MediKnit* consists of (a) a design tool for creating active compression gloves and (b) a designed device with actuators that can be programmed to meet individual needs and address hand edema. A *MediKnit* device being used by a patient is shown in (c).

Current rapid prototyping in medical domains relies on rigid 3D-printed materials, lacking flexibility, customization, and clinician-led input. This paper introduces *MediKnit*, a novel approach for the fabrication of soft medical devices, addressing critical limitations in existing design processes for medical devices. *MediKnit* provides a design tool empowering clinicians to personalize fabric-based devices for hand edema. This tool allows clinicians to adapt the design to individual patients' demands, thereby enhancing the overall effectiveness of therapy. The *MediKnit* device created by this tool consists of a machine-knit

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glove with active compression, which is programmable through a custom PCB. This device facilitates the mobilization of edema. To illustrate the practical implementation of our approach, this paper presents case studies involving six patients experiencing hand edema. The results demonstrate the adaptability and feasibility of our process for developing soft medical devices, highlighting its potential to broaden accessibility, facilitate personalized solutions, and empower clinicians as active medical makers.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**.

Additional Key Words and Phrases: Medical making, Design tool, Textile-based device, Compression device, Hand edema, Robotic textiles, Fabrication, Workflows, Case study, User study

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1 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 Lakshmi et al., is born from an attempt to use technical fabrication processes and 3D printable materials in the medical field [29]. This concept underscores the accessibility of digital fabrication for occupational therapists (OTs), physical therapists (PTs), and clinicians to engage with these tools [21]. However, the current process for developing medical devices is characterized by certain limitations. First, it focuses on producing monolithic and inflexible devices through 3D printing technology, which restricts applications to rigid devices for orthotics or rigid contraceptives [21]. Inflexible and bulky 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 [17] but also encompasses diverse hand shapes. 3D-printed devices cannot effectively compress edematous hands, and clinicians' input is required to address variability, so personalized 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 [40, 41], 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.

2 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 [41]. Massages are effective but can be costly, ranging from 50 USD to 150 USD per session [47]. Pneumatic sleeves, with proven efficacy [41], 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 1). 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.

Table 1. 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. [22]	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. [39]	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. [48]	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. [16]	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. [28]	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

3 Related Work

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

3.1 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 [29]. 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 [20], which leverages domain-specific knowledge, including clinical knowledge, in operating digital 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.

3.2 Treatment Regimens of Hand Edema

The presence of swelling in the hand, as previously discussed in Section 2, 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 [8]. 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 [41]. 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 [37]. 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 [8]. 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 [8, 41]. 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.

3.3 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 [4, 5, 19, 32, 44, 50, 52, 58, 59], weaving [7, 51], sewing [30], and

felting [45]. 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 [23, 46] and knit interfaces, including flexible sensors [2, 55, 56, 59], actuation [3, 6, 25], haptic and tactile sensation [5, 27, 34], shape-changing interfaces [6, 33], and robotic textiles [25, 33]. It supports a diverse range of functional applications recently to include medical devices [26]. 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. [38] presented a compiler to turn high-level shape primitives such as tubes and sheets into low-level machine instructions, and Narayanan et al. [42] 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 [24, 43].

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, (i.e., a pixel could represent anything from a single stitch that occupies less than 1mm^2 to a larger area, depending on user specifications) without involving clinicians in the technical details of knitting. Moreover, in clinical applications, timely device delivery with minimal iterations is crucial [21], a goal actively supported by *MediKnit*.

4 *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 2), 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.

4.1 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) [14]. 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 together [54]. 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.

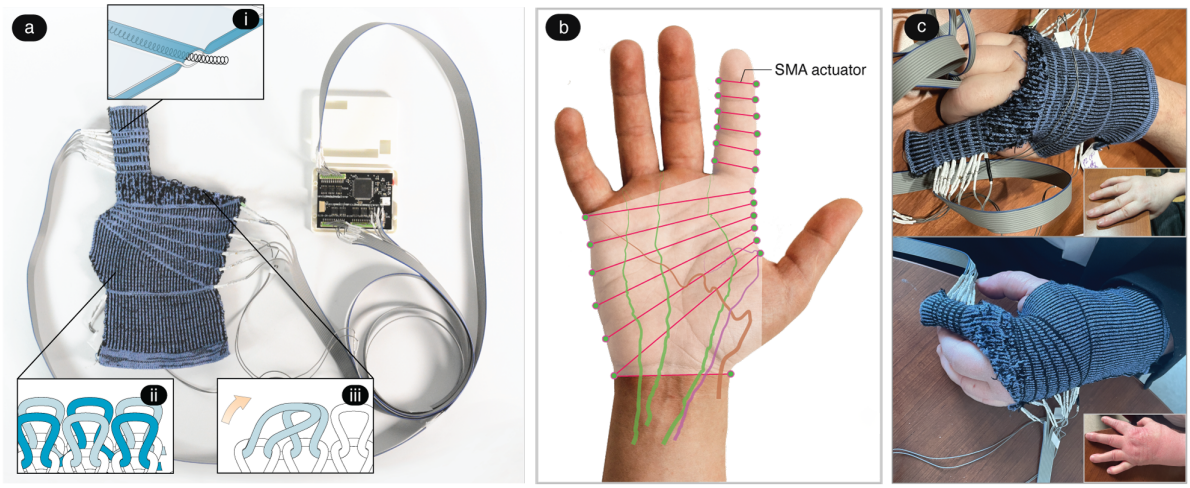

Fig. 2. (a) *MediKnit* system consists of a knitted substrate, 13 shape memory actuators, and hardware. (i) Substrate creates "channels" for actuators, (ii) accommodates swelling in the prominent direction, and (iii) covers hand corners. (b) The 13 actuators are designed based on lymphatic vessels distribution. (c) *MediKnit* device on participants with hand edema. Superimposed pictures show visible compression marks.

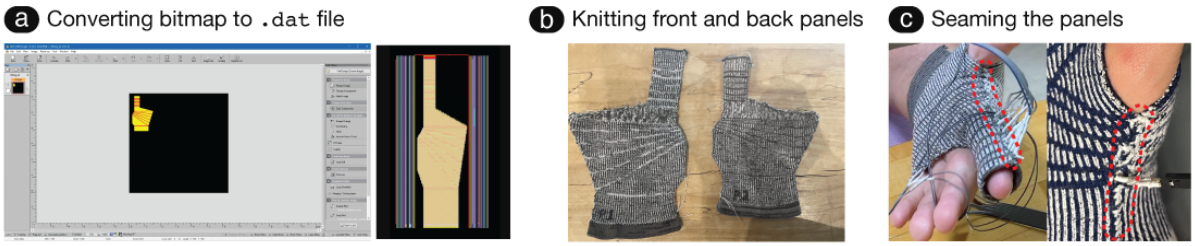

Fig. 3. (a) The conversion of a bitmap file to a .dat file is performed using KnitPaint. (b) The .dat file is knitted as front and back panels. (c) The panels are seamed to form *MediKnit* device.

4.1.1 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 [41]. 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.

4.1.2 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* [27]. 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 2). 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.

4.2 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.

4.2.1 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 [53]. 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 [35]. 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.

4.2.2 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% [49]. 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 4). 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.

4.2.3 The Index Finger. For the index finger, we reconducted the compression test from the literature [26] as we shared identical specs of shape memory alloy springs and knit substrate structure, and verified that the results

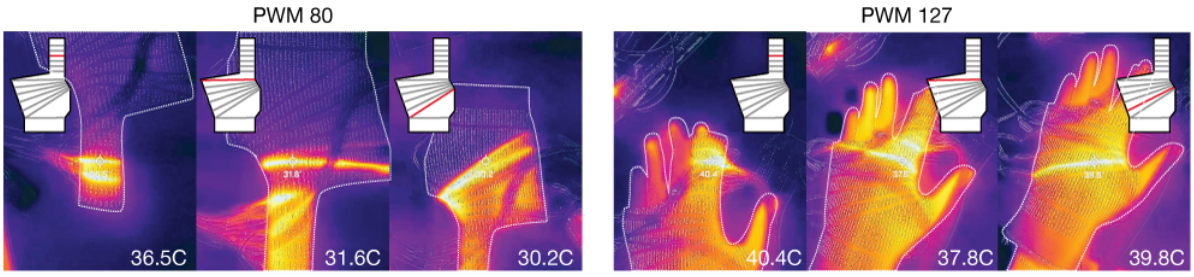

Fig. 4. Left: Heat map of the actuated glove placed on a table. At a PWM of 80, SMA springs on the finger reached 31.6°C and on the palm 30.2 - 31.6°C. Right: Heat map of the actuated glove while worn on the hand. At a PWM of 127, finger temperatures hit 40.4°C and palm temperatures 37.8 - 39.8°C, creating 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.

were replicable. We followed the reported number of compression bands of six and the duration of compression of thirty seconds in the study.

4.2.4 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 4.2.1. 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 5). 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 5), 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 5). 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 7), 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.

4.2.5 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 [11]. We also incorporated a silicone mock hand due to its elastic properties, which closely mimic human skin [15]. 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

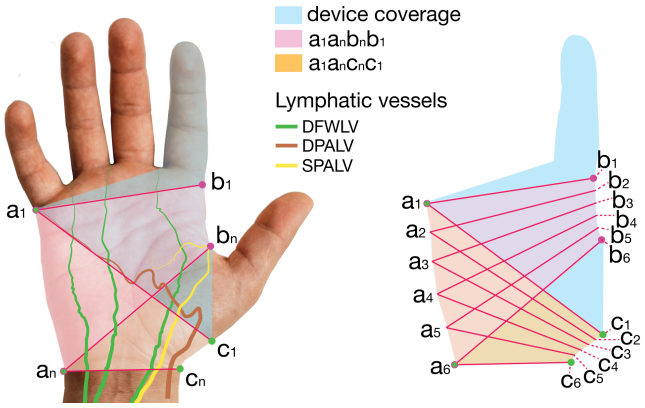

Fig. 5. The figure on the left is adapted with permission [35]. Deep finger web lymph vessels (DFWLV) run from the palmer side of the hand and turn their courses to the dorsum side of the hand. These vessels run short after crossing the web spaces. Similarly, one or two of the superficial palmar arch 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.

system (Figure 6). 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 6 (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 2. 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 that cross it, namely $\overline{a_i c_j}$ ($i < 3$, $j < 3$). Following this method, we finalized 7 bands: $\overline{a_1 b_1}$, $\overline{a_2 b_2}$, $\overline{a_3 b_3}$, $\overline{a_4 b_4}$, $\overline{a_5 b_5}$, $\overline{a_6 b_6}$, and $\overline{a_6 c_6}$.

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 6 (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.

4.3 *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,

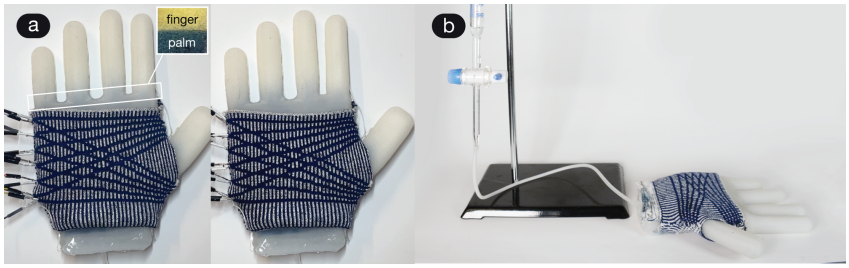

Fig. 6. (a) Experimental setup to observe backflow displacement of fluid from the fingers to the hand. The sponges utilized exhibited uniform porosity. The image on the right shows no discernible displacement of pigment from the onset (left). (b) Setup to characterize compression bands in the palm. The silicone mock hand was positioned flat embedded with 12 SMA compression bands.

Table 2. 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

allowing freedom for individual intensity of compression (Figure 2). 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 4.2.5). 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.

4.4 *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 7).

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 8).

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/

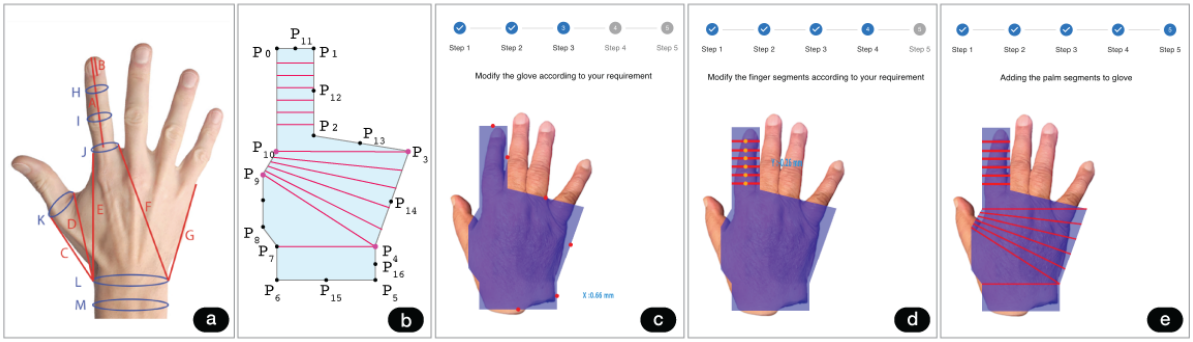

Fig. 7. *MediKnit* design tool provides: (a) Visual guidance for thirteen hand measurements for customization; (b) Backend algorithm converts the measurements to 18 coordinate points; (c) and (d) A glove template is generated based on these coordinates, with options for therapists to adjust both the template and SMA channels; (e) The design tool then creates a machine-readable file.

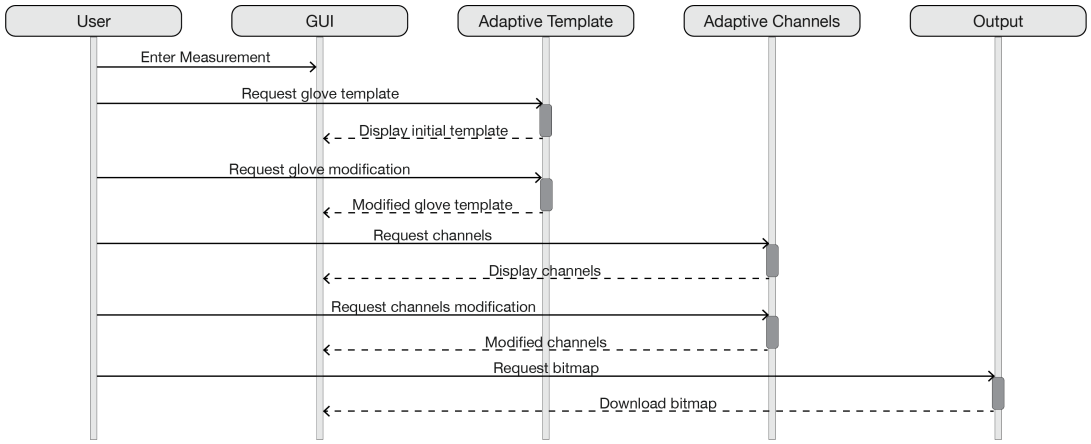

Fig. 8. Sequence diagram of *MediKnit* design tool.

4.4.1 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 7 (a), (b)). To facilitate this process, the design tool provides visual guidance for these measurements in the initial step, as illustrated in Figure 7a. 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.

4.4.2 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 7c), 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.

4.4.3 Adaptive Channels. As outlined in Section 4.2, 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.

4.4.4 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 7e). 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.

5 *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 9), and (2) the **clinician-led workflow** using *MediKnit* design interface (Figure 10). We obtained insights into each workflow through interviews with technicians and clinicians.

5.1 Participants

In both workflows, we recruited 6 participants experiencing hand edema from Site A and Site B. This paper presents case studies featuring patients from Site A in the knitting technician-led workflow, whereas cases involving Site B patients were reported through the clinician-led workflow. Site A, a regional rehabilitation clinic, specializes in hand therapy and lymphedema management programs. Site B, 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 3. 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	Site A
P2	40	M	Home maintenance	Muscle stiffness and hypersensitivity	Site A
P3	53	F	MEM, hand therapy	None	Site A
P4	73	M	Manual massage	Muscle spasticity	Site B
P5	78	M	OT, fine motor therapy	Insensate hand	Site B
P6	65	M	Home maintenance using Bioness	Muscle spasticity	Site B

5.2 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.

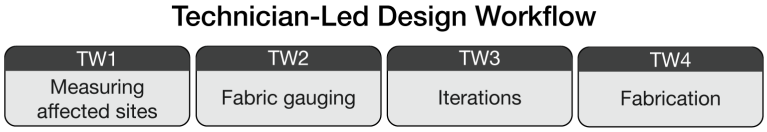

Fig. 9. Technician-led design workflow.

5.2.1 Knitting Technician as a Domain-Expert Participant. In addition to the three patient participants recruited from Site A (P1, P2, and P3, Table 3), 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.

5.2.2 Protocols. The protocol for this workflow comprised four steps. The devices were tailored to three patient participants recruited from Site A (Table 3). 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 3) recruited from Site A participated in a survey, providing details on basic demographics, their standard of care, frequency of therapy, and 13 anthropometric measurements of the hand (Figure 7 (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.

5.2.3 Analysis. The pre-survey from TW1 (Section 5.2.2) 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.

5.2.4 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 remeasured 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.

5.2.5 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 5.2.4) 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.

5.3 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.

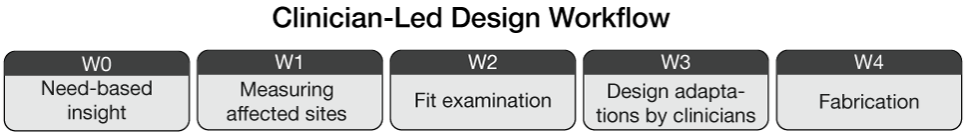

Fig. 10. Clinician-led design workflow.

5.3.1 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 4).

Table 4. Information of clinicians participated in this workflow.

Code	Age	Gender	Experience (years)	Care Site	Code	Age	Gender	Experience (years)	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					

5.3.2 Protocols. The protocol for this workflow consisted of five steps (Figure 10). 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 4) from Site B to participate in a survey. They were given 10 minutes to answer 4 questions (Table 5). 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 5, Q1), the requirements for a digital tool to aid their design process (Table 5, Q2), specific features that would assist them if included in a design interface (Table 5, Q3), and their preferences between optimized and customized design suggestions (Table 5, Q4). This information contributed to the development of the design interface discussed in Section 4.4. 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 Site B 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 Site B, 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 6).

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.

5.3.3 Analysis. The researchers collected and analyzed clinicians' responses from the need-based survey (Table 5 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.

5.3.4 Preliminary Need-Based Insights. Insights from the need-based survey (W0) were obtained after collecting and analyzing completed questionnaires. Regarding question 1 (Table 5), 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 5 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).

Table 5. Need-based insights.

Questions	Options	Responses
Q1: Does edema show more variability across patients than other conditions? Please elaborate (Sec 5.3.4)	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 and tried on the patient's hand	5
	Both, before and after the device is manufactured	4

5.3.5 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.

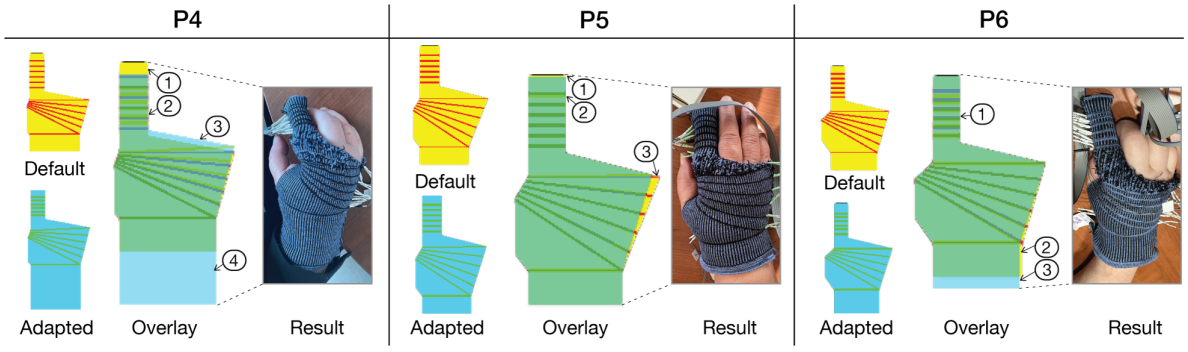

Fig. 11. Visual representation of machine-readable knitting files showcasing the default design generated by the *MediKnit* design tool (utilized in W2, labeled in yellow) and the modified design by therapists labeled in green.

- **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 11, P4. ①) and metacarpophalangeal (MCP) joints (knuckles) (Figure 11, P4. ③) and then lengthened the cuff to encompass the entire wrist (Figure 11, P4. ④). Additionally, she fine-tuned the first channel on the index finger to align precisely below the nail base (Figure 11, 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 11, 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 11, 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 11, 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 11, P6. ②) and cuff (Figure 11, 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 11, 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.*

5.3.6 Results. Clinicians' responses to the semi-structured interview (Table 6) were analyzed and categorized into three themes, which are discussed here.

Table 6. 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.

5.4 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 [21]. 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 7. 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 *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.

6.1 Participants

We recruited six participants retained from the earlier case study (Section 5.3). 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 3).

6.2 Apparatus

As explained in Sections 5 and 6, 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 4.2.2.

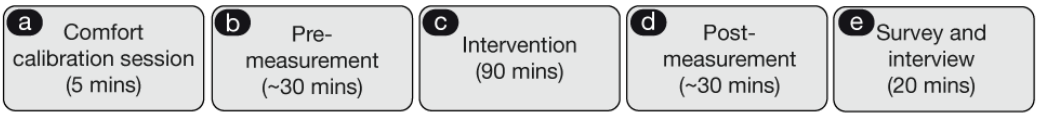

Fig. 12. The flowchart of *MediKnit* study protocol.

6.3 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 12 (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 12 (c)). During this period, every 13 SMA bands (as detailed in Section 4.3) 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 12 (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 [12, 13, 31]. 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 12 (e)).

- **Volume Measurement**: As one of the common measurements [26, 40], 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.

6.4 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 [57] 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* [9]. 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 8. 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)

Measurement	ICC and [95% CI] of **baseline**	ICC and [95% CI] of **post**	Measurement	ICC and [95% CI] of **baseline**	ICC and [95% CI] of **post**
Volume	0.999 [0.851, 0.999]	1.000 [0.949, 1.000]	Figure of eight	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]

6.5 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 8) for measurement reliability. We then plot descriptive data (Figure 13) and report statistical analyses.

6.5.1 Measurement Results.

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 [18]. 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 [36]. 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 [10]. 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 <

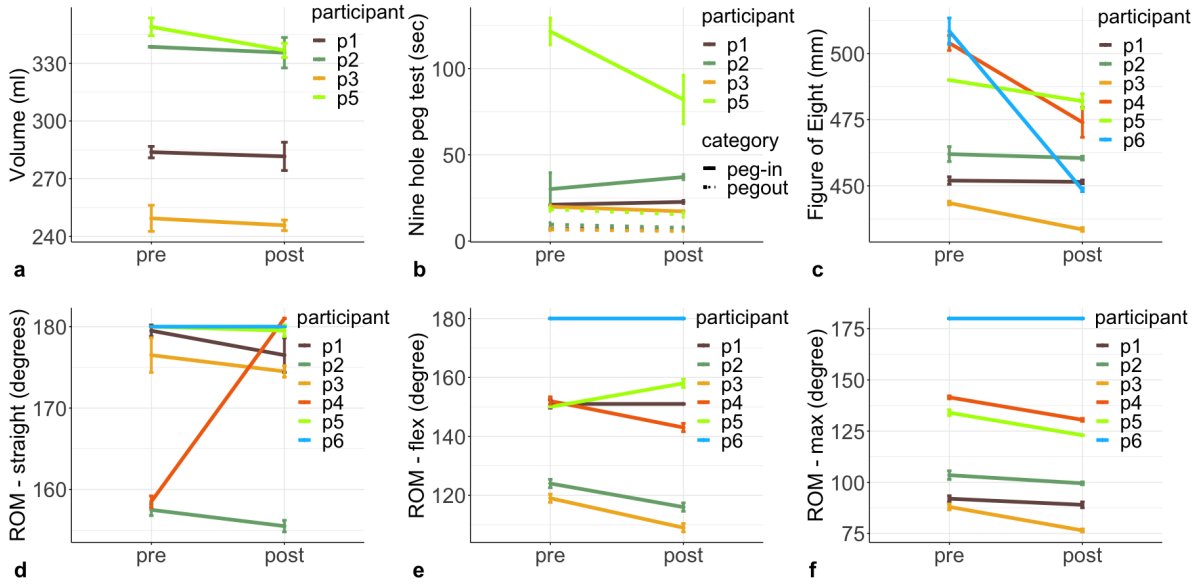

Fig. 13. (a) The volumetry indicated a decrease in volume after the intervention in the descriptive data. (b) 9HPT showed a notable difference in the two activities: putting 9 pegs into the holes (trial: in) and taking them out (trial: out). (c) In the figure of eight, all participants showed a descriptive 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.

.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.

6.5.2 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 9). 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:

- **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.

Table 9. 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

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).

7 Design Recommendations

An Alternative to a Prescriptive Model. The *MediKnit* approach adopts a partial "prescriptive approach [21]", 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.

8 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 [1] 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.

9 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 [29]. 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.

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