KnitDema: Robotic Textile as Personalized Edema Mobilization Device

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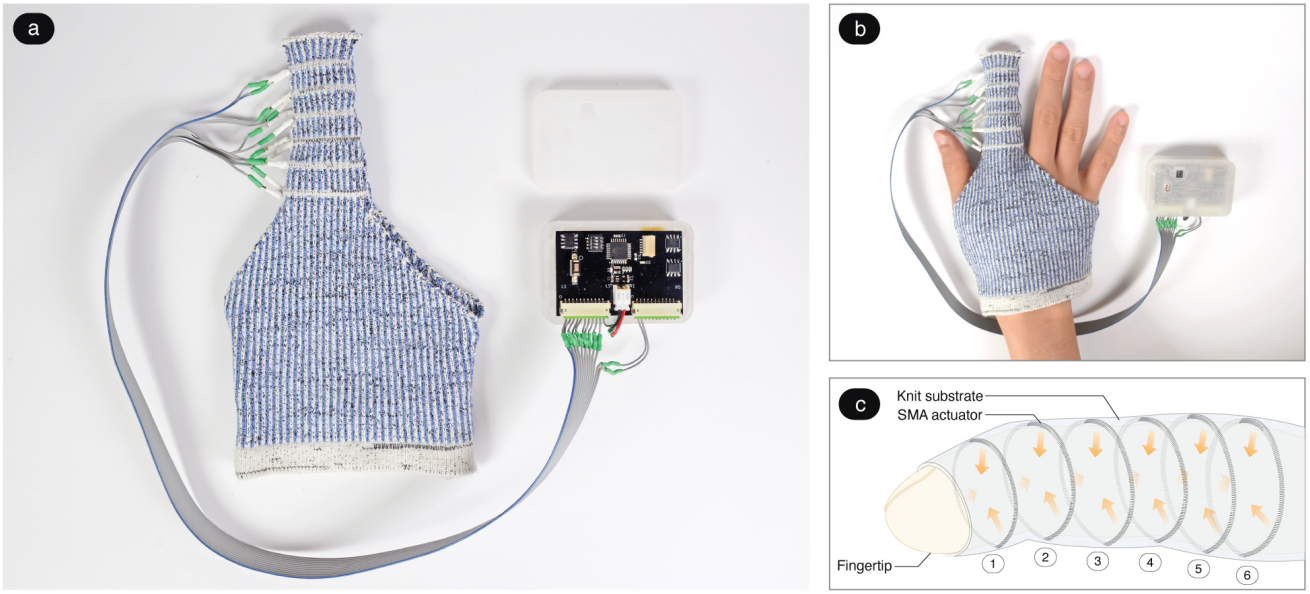

Figure 1: KnitDema consists of a machine-knit semi-glove and hardware (a) to compress edematous hands sequentially. The device covers the index finger (b) and uses embedded shape memory alloy (SMA) bands to mobilize edema fluid from the fingertip to the base (from 1 to 6 in c). A human-subject case study demonstrates the feasibility and potential efficacy of the device.

ABSTRACT

Hand edema, defined as swelling of the hands caused by excess fluid accumulation, is a pervasive condition affecting a person's range of motion and functional ability. However, treatment strategies remain limited to time-consuming manual massage by trained therapists, deterring a widely accessible approach. We present KnitDema, a robotic textile device that allows sequential compression from distal to proximal finger phalanges for mobilizing edema. We machine-knit the device and integrate small-scale actuators to envelop granular body locations such as fingers, catering to the shape of the hand. In addition, the device affords customizable compression levels through the enclosed fiber-like actuators. We characterize compression parameters and simulate the shunting of edema through a mock fluid system. Finally, we conduct a case study to evaluate the feasibility of the device, in which five hand edema patients assess KnitDema. Our study provides insights into

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the opportunities for robotic textiles to support personalized rehabilitation.

CCS CONCEPTS

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

KEYWORDS

Wearable Computing, Hand Edema, Rehabilitation Device, E-Textile, Robotic Textile, Haptics, Compression Device

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1 INTRODUCTION

The COVID-19 pandemic and at-home social isolation have highlighted the need for personalized healthcare strategies that can empower people to manage non-life-threatening medical conditions without frequent hospital visits. Prolonged hand edema can affect the range of motion, active movement, and everyday human functional ability. For example, reports indicate that 73% of persons post-stroke have experienced hand swelling and that it severely impacted the quality of life [7]. Hand edema is caused by an abnormal buildup of interstitial fluid and can occur throughout the hand [22]. Current edema treatment or management is provided in clinical settings, often requiring manual massage by physical or occupational therapists (PT/OT) for mobilizing edematous fluid [41, 42]. While manual massage can be customized to individual patient needs, the cost of highly trained personnel providing labor-intensive treatment has deterred a scalable and widely applicable strategy. Other common treatments, such as intermittent pneumatic compression (IPC) devices, are extremely bulky and not customizable to individual anthropometry. Thus, there is a lack of *cost-effective*, *customizable*, and *portable* edema treatment strategies for use outside a hospital or clinic setting.

To close this gap, we present KnitDema, a *robotic textile* system that provides sequential compression across finger phalanges for mobilizing hand edema. Robotic textile is an emerging form of fabric-based soft robots that enable "sensing, actuation, and stiffness control" in "a single conformable fabric substrate" [9, 10], creating a new platform of robots to offer compliant structures compatible with wearables.

Robotic textiles can be especially suitable to the needs of hand edema treatment in terms of (1) individual customization, (2) accessibility, and (3) comfort. Diverse etiologies and presentations of edema in individuals are among the main challenges that make hand edema difficult to treat; individuals must comply with different treatment timelines and regimes. The diverse hand shapes and swelling presentations are compounding this problem, making standardized treatment difficult. KnitDema caters to individual medical needs and anthropometry of the hand by offering programmable compression parameters and leveraging machine knitting which can fabricate made-to-measure devices. Highlighting accessibility, KnitDema can be programmed to deliver a sequence of automated actuation from the comfort of the patient's home, alleviating the need for costly and frequent therapy visits to clinics. Further, unlike IPC, robotic textiles are comparably inexpensive and easy to fabricate with standard textile machinery. Finally, KnitDema affords superior comfort because it is breathable and comfortable to wear. Compliant fabric and small-scale actuators allow the device to reach granular parts of the hand without fatiguing the hand in long-term use. The textile-based device does not encumber patients with bulky bladders, compressors, or oversized form factors.

To understand patient's needs from multiple perspectives, we adopt a co-design process [17, 29, 30] in which a collaborative team of human-computer interaction (HCI) researchers, rehabilitation physicians, and hand therapists iteratively developed the device and study protocol over 1.5 years. Integrating slim shape memory alloy actuators in machine-knitted textile structures, KnitDema affords sequential compression by actuating low-profile substrate attached to a portable printed circuit board (PCB) controller. We identify compression parameters for the developed system and characterize them in-vitro utilizing a mock fluid displacement system. This culminates in a human subject case study with persons with hand edema to understand the feasibility of the KnitDema system. Throughout this longitudinal co-design process, the researchers and physicians gained insight into managing and treating edema from an interdisciplinary perspective. We further reflect on this process to benefit co-design processes in other realms of health technology. We make the following contributions:

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

2 RELATED WORK

2.1 Treatment Regimens of Edema

Various disorders can cause edema to manifest with different presentations on the body. While treatments of edema can vary by individual, "mobilization of excess fluid" is the primary goal in treating edema. Literature identifies common treatment regimens as active compression and manual edema mobilization (MEM) [41, 42]. Active compression involves electrical components that exert forces on the body to move interstitial fluid through the lymphatic system. Intermittent pneumatic compression (IPC) is one of the most

widely applied devices of this sort [21], in which pneumatic chambers wrap around the limb, compressing it as the chambers inflate. To mobilize fluid, subsets of IPC come with capabilities to inflate chambers sequentially [49] and with force gradients [15]. IPC devices have demonstrated effectiveness for a wide range of diagnoses from breast carcinoma [60] and lymphedema [18, 70] to deep-vein thrombosis [1]. Nonetheless, the sheer size and bulkiness of IPC devices make them difficult to treat granular parts of the body, such as fingers or hands. Moreover, the uniform form factors of IPC prevent treatment from catering to individual body shapes.

Another prominent method to reduce edema is manual edema mobilization (MEM) [6, 50], or retrograde massage therapy, which involves therapists applying light traction on the skin along lymphatic pathways. MEM allows more delicate management and accommodates patients' body shapes as therapists rub the convexes and concaves of the body. MEM has also proved efficacy across lymphedema [33], and sub-acute hand edema [42]. However, MEM therapy can be difficult to perform without trained therapists.

Outside common treatment regimens, there are other ways to reduce swelling in the extremities. Fluidotherapy [26] is one, which involves fine solid particles flying in a hot dry whirlpool to stimulate the body. Analogous to IPC, fluidotherapy requires tethered devices that take up space and are not readily available outside clinics. There are also compression garments, and Kinesiotaping [5, 31], or taping, for passive compression. While passive compression can be more accessible and readily available, literature renders it as more of a maintenance regimen than active management to reduce swelling due to decreased efficiency and prolonged intervention time [31].

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

2.2 Robotic Textile in Medical Applications

As defined in the literature, robotic textiles enable sensing, actuation, or stiffness control embedded in a single compliant substrate [10]. In particular, robotic textile with actuation capability brings attention to the potential of shape-changing textiles for versatile applications. Actuators with small footprints or "functional fibers" [9, 10] give motion to robotic textiles for load-bearing [69], haptics [59], thermoregulation [63, 65], hand rehabilitation [11, 19], gait assistance [61], or therapy [62]. As an emerging form of planar and soft robots, robotic textiles typically serve as an embodied contraption worn by the wearer. The textile-based contraption enhances [54] and rehabilitates [56] the wearer's muscle capacity from proximity to the skin. While there have been approaches to integrate actuators into woven fabrics [36, 59], manipulation of woven textiles remains limited due to the inherently inextensible nature of weaves. Knit stands out as its versatile loop-by-loop structure enables multiple degrees of freedom in motion when coupled with desirable actuation [39] and anisotropic manipulation when used in conjunction with other strain-limiting layers [45].

Robotic knit is an attractive medium to be used in conjunction with suitable actuators, especially for rehabilitation applications. In the past, many approaches have focused on aiding the musculoskeletal movement of muscles through pneumatic actuators or bladders. In those applications, knit selectively allows strain of the pneumatic actuators to help with grasping [19, 66, 73], locomotion [61], abduction or adduction [46, 73]. To date, there has been little emphasis on reducing the scale of this rehabilitation equipment while maintaining adequate force generation. However, growing interest in rehabilitation devices has started to move the field toward this sophisticated manipulation of muscle [53] enabled by high DOF or small-scale actuators [34].

Containing actuators within a conformable substrate, KnitDema's goal aligns with this transition; the project aims to treat swollen fingers, which may encumber patients if using bulky actuators from the above conventional contexts. While the fiber-scale actuators [34] do reduce device size, the need for a portable pump and tube does not align with KnitDema's objective to be a small-footprint device. We build on and further extend the fabrication introduced in [35], in which shape memory alloys were integrated inside a knit substrate to render tactile feedback, extending it for medical application.

2.3 Co-Designing with Clinicians

As with other diseases, there are no two identical manifestations of edematous hands. It is thus vital to understand patient needs through clinicians and therapists to fabricate treatment devices that can accommodate the attributes of individuals. In interdisciplinary studies in HCI, co-designing methods [17] in the past have helped researchers channel domain-specific knowledge and insights to projects, yielding fruitful results.

In the past, researchers and therapists have co-designed assistive technologies [29, 30] to enable digital fabrication and methods for rapid prototyping for patients. Through observing and interviewing clinicians, researchers gained insights and worked collaboratively with therapists to deliver assistive technologies that meet patients' needs. In a similar clinical context, researchers have utilized "design cards" to help therapists conceptualize telehealth media that could potentially be deployed in their practice [32]. After holding onto the cards for a week, therapists rejoined researchers again and shared perspectives on how the telehealth media can be considered invasive. Researchers have also conducted long-term ethnographic studies with patients in an attempt to enhance current implanted cardiac devices (ICD) [2]. Researchers provided ICD patients with a web platform and an app in which patients would voice-record their clinical and mundane experiences with their ICDs. Accumulated feedback helped researchers gather information on the current cardiac devices and brainstorm potential improvements.

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

3 OUR CO-DESIGN WORKFLOW

The co-design process in this research covered the end-to-end workflow from early brainstorming of the device to the human subject user study in which persons with hand edema experienced the device. We adopted co-design [17, 29, 30], and research through design [74] to inform and complement our workflow. Co-designing process spanned from building the *device* to developing the *device-patient experience* during the user study. The process involved a collaborative team of HCI researchers, rehabilitation physicians, and physical and occupational therapists (PT/OTs) from Cornell University (CU), Weill Cornell Medicine (WCM), and Cayuga Medical Center (CMC), respectively. The HCI researchers spearheaded the development of the device, characterized compression parameters, and wrote an IRB-approved protocol for the user study, with guidance from rehabilitation physicians. Therapists at CMC contributed practical knowledge on the mechanics of manual edema mobilization, current management of edema from a patient's home, and the logistics of edema therapy in general, and supported the recruitment of patients for the study.

Exchange of Expertise. This early phase of the co-design process was in part informed by [29, 30, 55], in which the parties that *produce* the device and patient-device experience come together to share expertise and domain-specific knowledge to establish collective research goals while keeping the *recipients* (i.e., patients) of the product in mind. HCI researchers held bi-weekly remote meetings with rehabilitation physicians starting from April of Year 1, as CU and WCM are situated in different cities. HCI researchers began by introducing the concept of robotic textiles, actuation mechanisms, and control, along with the mechanical properties of shape memory alloys, constraints in machine knitting, and early conceptualization and schematics of the device. Physicians shared the causes and clinical presentations of edema, current treatments, and the downsides and upsides of those treatments. While the bridge between the two teams moved the development of the device along, HCI researchers were keen to learn about the actual procedure of therapy in practice and the role of therapists in engaging with patients. The researchers reached out to therapists at a local rehabilitation clinic, CMC, which served as the primary recruiting site for the user study, to understand firsthand what engaging with prospective participants entails. HCI researchers and therapists at CMC convened on a regular basis before and during the user study to conceptualize desirable patient-device experiences. Through the established link between the two parties, researchers learned the average duration and program of therapy, how to "work" the swollen hand to massage tissues along the nodal pathway as the excess fluid drains out from the hand, and how other external factors such as temperature and humidity affect patients.

Cross-Disciplinary Iterations. These concurrent discussions across different institutions helped expand the scope of the project's co-design beyond HCI, and to include therapists and physicians in both the design and implementation processes. Convening on a regular basis helped the teams accelerate iterations. Among HCI researchers and rehabilitation physicians, (1) the wearability and portability of KnitDema, (2) testing compression elements, and (3) study protocol were among the main agenda for iteration. In particular, to identify ways to simulate edema mobilization from the hand to the upper lymphatic stream, both teams brainstormed on a fluid-based mock system that mimics the shunting of interstitial fluid outside of the closed vascular system [3]. Researchers and physicians ensured that the mock fluid system (Figure 5) provided similar fluid dynamics as the pressure applied by the device. Physicians and researchers also designed a custom volumeter unique to the hand's index finger. The teams wrote and iterated the study protocol and ran pilot studies with non-patients. In the meantime, researchers and therapists at CMC discussed the logistics of the protocol for the human subject study and patient-user experience throughout the study. With therapists, researchers refined the protocol for a smooth transition throughout each step of the study. Toward the end of the longitudinal process, physicians visited CU from WCM to test the finalized device design. This culminated in all three teams convening at CMC and WCM (Figure 2) to run a human subject study and gather insights from the patients.

4 DESIGN CONSIDERATIONS: TOWARDS A PERSONALIZED REHABILITATION DEVICE

In this section, we discuss the design considerations of the system we have developed, which was based on extensive bi-weekly discussions between our research team of rehabilitation physicians and HCI researchers, regular consultation with therapists, and also a review of relevant literature [16, 21, 25] throughout a 1.5 year period.

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

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

Portability. Both rehabilitation physicians and therapists highlight the lack of portable treatments for edema [21, 52], despite the need for an extended period of management. Portability is a crucial factor

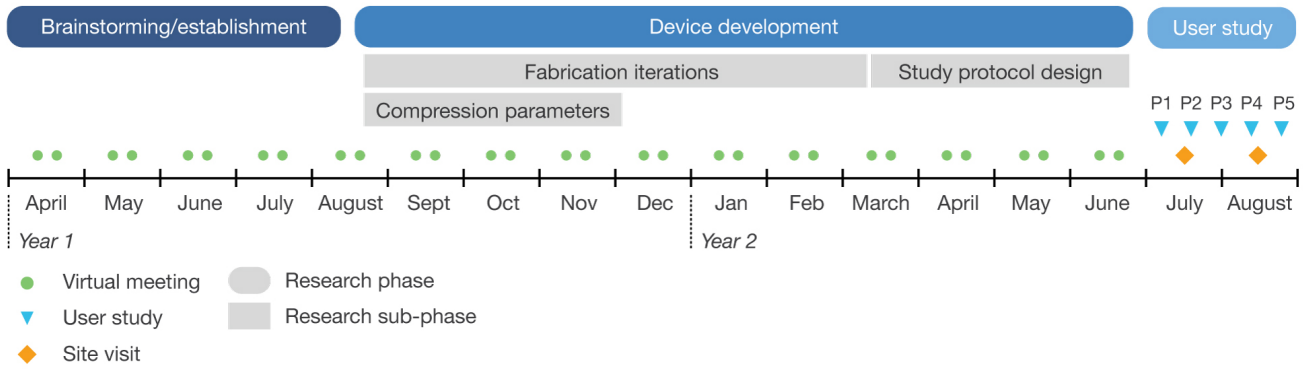

Figure 2: Timeline of co-design workflow

in developing the device so that the device can be implemented in settings outside clinics without the attendance of therapists beyond the initial prescription. We seek small-scale actuators that can be integrated into the fabric and powered by a small-footprint battery while having sufficient force to compress the hand.

Comfort and Wearability. Another prominent goal is to make sure the device is comfortable and wearable. Rehabilitation physicians share how donning and doffing of pneumatic compression devices could encumber patients despite their effectiveness [23]; compression garments boast effortless donning and doffing while being less effective in mobilizing edema [21]. We aim to achieve both aspects by making donning and doffing the device undemanding but achieving active and sequential compression.

5 DESIGNING KNITDEMA

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

5.1 Knit Fabric Substrate

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

Knit Structure Design. The knit substrate is where the shape memory alloy (SMA) springs are integrated to compress the hand. We build upon the *tubular jacquard structure* [35] to integrate micro-SMA springs. The tubular structure (Figure 3 (a) i) creates hollow pockets which can run in all directions to create free-form patterns that can intersect with each other. The width of the pockets can also run as small as one stitch, or less than a millimeter, to as wide as a few inches, accommodating a wide range of actuator scales. While the active compression is provided through the integrated actuators (described in Section 5.2), the knit substrate affords *passive* compression. For the substrate outside the active area where the SMA springs are enclosed, we use yarns with extensive elasticity in an *interlock structure* (Figure 3 (a) iii), which exhibits constrained longitudinal strain but higher circumferential strain to help the substrate withstand enlargement of the hand. In addition, through machine knitting software, Apex 3, minuscule details of the design can be adjusted, helping size the device to varying shapes of the hand and specific body landmarks. Rehabilitation physicians pointed out that swelling could be disproportionate across the finger, making the finger base thicker than the fingertip. We used *shaping* technique via the Apex 3 to taper the finger sleeve and fit the tapered fingertips. We also used this *shaping* technique (Figure 3 (a) ii) to cover the palm and wrist while carving out an opening for the rest of the fingers.

Passive Compression. When the device is not actuating, a moderate amount of constant pressure is still applied to the hand. This passive compression is attributed to the knit fabric. Passive compression is a commonly administered treatment strategy in treating hand edema. Popular edema management tools that use passive compression include string wrapping, taping, Isotoner glove, or Coban wrapping [42]. Passive compression of KnitDema depends on factors including *(1) yarn properties*, *(2) knit fabric structure*, *(3) knit loop length*, and *(4) the fit of the device to the hand*. One could up the passive compression by adding yarns to the substrate. Adding additional elastic yarns leads to denser knit loops, which draw in tightly after being released from the knitting bed. Alternatively, the substrate could be knit with structures that have less ability to expand. Decreasing the loop length is another way to alter how tight the substrate is. As the lengths of the interconnected loops are shortened, the knit structure forms tighter loops, resulting in a denser structure. Finally, one could improve passive compression by sizing the device tightly to the hand. In our final implementation, we use Puma, Sting, and Jaguar yarns, sourced from Silk City. We

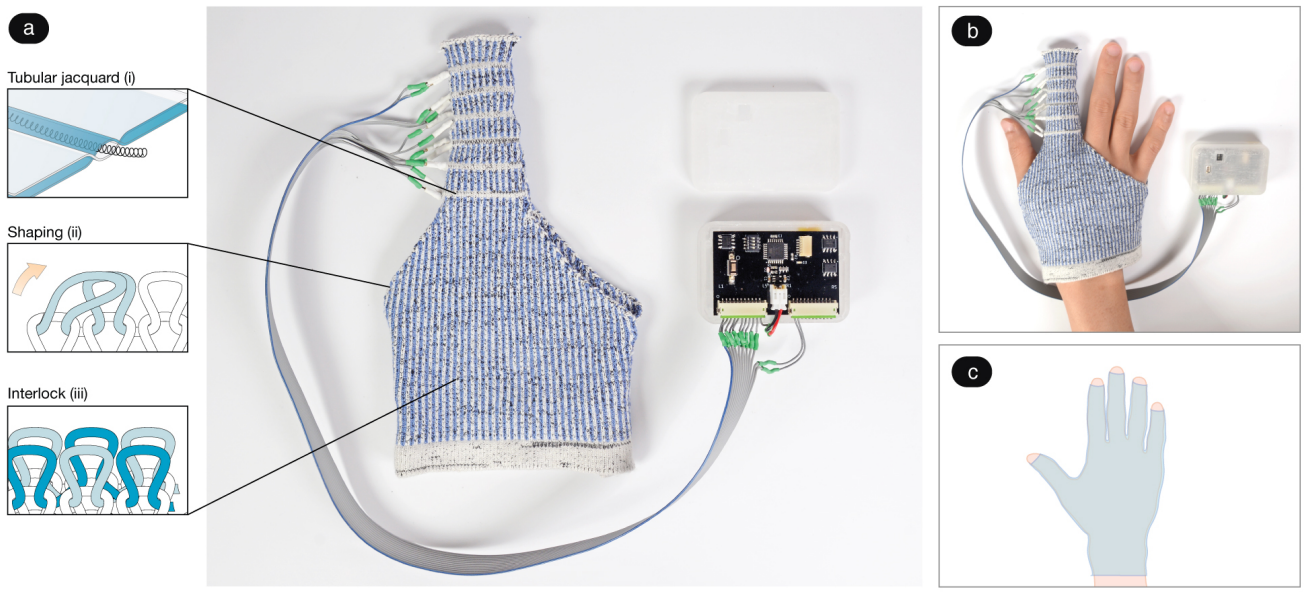

Figure 3: (a) KnitDema system in which the finger sleeve is knit with a combination of (i) tubular jacquard, (ii) shaping, and (iii) interlock structure. The tubular structure creates "channels" to incorporate SMA springs. The substrate also uses a shaping structure to conform the substrate to the rest of the fingers. (b) KnitDema finger sleeve device worn on a hand. (c) Future implementation of a full-hand KnitDema device.

set the loop length of the devices as 30 on the knitting machine for the desired passive compression effect.

5.2 Fiber-Like Actuators for Active Compression

For the device to serve as a compliant robotic textile and an active compression system, we consider miniaturized and small-footprint actuators that exhibit low stiffness, such that they can easily wrap around the finger and fit into the knit fabric. Prior works have used soft bladder actuators to be fitted around the limb [37, 48, 71] to apply pressure. However, these applications require inextensible layers to limit radial expansion [28, 48] or an external air reservoir that has limited portability [72]. These bulky devices pose tremendous difficulties when applied to granular areas of the body.

SMA Spring as Actuator. Materials that contract when electrically driven, such as shape memory alloys, have been used to generate compression stimuli in haptics [24, 35]. While shape memory alloy wire demonstrates favorable flexibility and minimal footprint, the limit in its strain restricts the material's load capacity. Twisted-coiled artificial muscles (TCA) exhibit comparable linear strain [47]. However, the required temperature range for glass transition exists far outside our application. Meanwhile, shape memory alloy springs demonstrate higher load capacity for compression, affording a wide range of applications [24, 40, 44, 57, 67]. SMA springs meet our needs for a low profile, lightweight, and high energy density actuator (Kellogg Research Labs, inner diameter: 0.5mm, wire diameter: 0.25mm, transition temperature: 45C).

Configuring SMA in Knit Substrate. Owing to free-form channels, a tubular jacquard structure can have SMA springs run through various shapes on the knit substrate. Our approach lays bands of SMA along the circumferences of the finger exerting tangential and normal forces. We explored vertical, cross, and slanted SMA configurations and compare the amount of water displaced from the pressure. The vertical configuration mobilized the most fluid with minimal energy. While one could configure SMA in complex curves to go around joints or bypass regions with dense pain receptors, our main goal is to maintain efficient load throughput [24]. As we emphasize the maximum load SMA can provide in a second, we aim to keep the energy to a minimum. Also, from a clinical standpoint, rehabilitation physicians emphasize "compression density" and more "granular compression points" to serve the device's purpose, given the tight-spaced finger geometry. All things considered, our primary focus in configuring SMA is to optimize compression density while keeping the load efficiency of each SMA maximal, which leads to the linear configuration of SMA (Figure 4).

Sequential Compression. The primary goal of active compression is to drain the edematous fluid captured within tissues through the lymphatic system. One of the most common treatments today involves manual edema mobilization (MEM), whereby the drainage is carried out by therapists manually massaging the swollen site [33, 42]. The key principle is to massage the edematous fluid from *distal* (situated *away* from the center of the body) to *proximal* (situated *nearer* to the center of the body), in which therapists clear the pathways above the affected body areas first. It remains

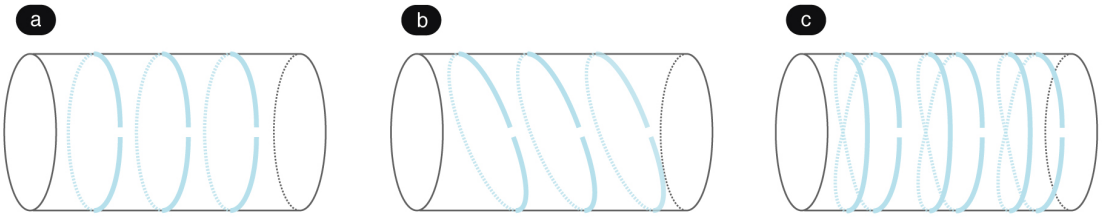

Figure 4: Each band in all configurations uses continuous SMA. As load throughput depends on the resistance of SMA, (a) is deemed the most efficient, followed by (b) and (c).

a time-consuming, labor-intensive, and expensive treatment to access. Another effective therapy, sequential intermittent pneumatic compression (IPC), follows the same principle: discrete chambers in a device compress the site of the problem from distal to proximal to shunt edema into veins upstream. Building on this principle, KnitDema configures several SMA spring bands dispersed evenly across the finger sleeve and applies pressure sequentially from distal (the tip of the finger) to proximal (the base of the finger).

5.3 Hardware

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

5.4 Envisioned Device-Patient Experience of KnitDema

We envision KnitDema to resemble a day-to-day glove in a patient's wardrobe without bulky controllers attached. Donning and doffing KnitDema should also be straightforward, and hence finding adequately elastic materials and knit structures was paramount. The overarching modus operandi of KnitDema was that parameters concerning compression would be programmed and set up by therapists and researchers before implementing the device for each patient. The envisioned device-patient experience is illustrated below.

Preparation of KnitDema. Before patients use KnitDema, therapists and rehabilitation physicians discuss and determine an adequate level of compression based on the patient's condition. Accordingly, the researchers would program an appropriate compression intensity (i.e., compression levels) into the device. The treatment session duration will also be determined here based on clinical acumen.

Usage of KnitDema. Because KnitDema sets out to be a compliant robotic textile and takes the form of a day-to-day garment, we expect patients to wear the device as they would wear their clothes. As KnitDema is customized for each patient with a structure allowing a higher elongation across the lateral direction, patients would don the device as they would put on a knit glove. Once patients don the device, they check if the distal SMA band of the sleeve was aligned close to the fingertip. After patients wear the device, they place their hands flat on a surface slightly below the heart level. We encourage patients to remain still during the use of the device. This is for the consistency of the blood flow to the hand (often emphasized in elevation therapy [43]), which is known to be correlated with swelling in the extremities. Finally, patients activate the device by pressing the button on the enclosure. KnitDema then runs its course as a robotic textile providing sequential compression for the duration of time set by clinicians. Once KnitDema completes its course, patients remove the device. As with the donning process, the doffing of the device does not involve demanding steps like pneumatic devices.

Long Term Usage of KnitDema. For patients with chronic edema, therapists would prescribe a desirable period of use per day and program a set level of compression. Once prescribed, patients would carry the device to wear in their spare time whenever swelling exacerbates, whether in the middle of the workday or before they go to bed. Prolonged use of KnitDema would especially be beneficial for patients who experience seasonal symptoms—exacerbated swelling in the hand when temperature and humidity are high— without burdening them with frequent therapies. Edema patients who have impaired mobility would also benefit from long-term prescriptions as they could manage the symptom remotely from home.

6 EDEMA MOBILIZATION PARAMETERS OF FLUID DISPLACEMENT

Providing effective yet safe compression levels is critical for mobilizing edematous fluid. To achieve optimal fluid mobilization, we conduct a series of experiments to determine suitable compression parameter values. We simulate the impact of parameters in a generalized setting. Since there are few established systems in the literature to simulate filtration and mobilization of interstitial fluid,

we looked at the usage of mock circulatory loop (MCL) systems, which have been utilized to test cardiac assist devices in-vitro. These loops typically include a water reservoir, piston pump, clamp, and air-trapped water reservoir where each component mimics the left atrium, left ventricle, blood flow resistance, and vessel compliance, respectively [12]. In contrast to the native cardiovascular system, however, our inquiry was not on blood circulation but instead on the return of interstitial fluid through the lymphatic system, which is outside of and distinct from the vascular system [3].

There have been approaches to simulate shunting of edema through the movement of air bubbles in water-filled tubes lying flat [58, 68]. However, the systems proposed do not account for the displacement in the finger. After consulting with two rehabilitation physicians and building on relevant literature, we landed on developing a mock hydraulic system where the external pressure applied to a compressible silicone finger saturated with water would drain the fluid out through a certain resistance (i.e., the tube outlet) and affect the reading of meniscus in the burette. This mock system also allowed us to observe the backflow of fluid, where the unloading of an SMA band led to immediate retraction of the fluid back to the distal of the finger. As our goal was to observe not only a single incident of compression but overall flare-ups and decreases in fluid displacement, this mock system helped us understand the trend of displacement caused by backflow. Our setup comprises a mock system with a water-saturated sponge and 3d printed bone encapsulated in the sponge, which totals the mass of an actual swollen finger. The mock finger is connected to a narrower tube, which is then connected to a burette such that the meniscus fluctuates as the pressure begins and diminishes (Figure 5).

Parameters for active compression, which influence fluid mobilization, include **PR1: Band Interval**, representing the time interval between single instances of SMA band compression, **PR2: Sequence Interval**, the time interval between completed sequences of SMA compression, **PR3: Compression Duration**, the duration of each SMA band compression, and **PR4: SMA Band Number** the number of SMA bands. These parameters are tested in a non-factorial method and in the above order. Starting with 3 SMA bands, tested first were the Band Interval (PR1) and Sequence Interval (PR2). Subsequently tested was the Compression Duration parameter (PR3). Finally, we tested the SMA Band Number (PR4) with identified aforementioned parameters. For clarification of the terms, *SMA band* represents a single SMA spring around the circumference of the finger; a *sequence* denotes the completion of one full compression cycle of all SMA bands in the fabric substrate; *interval* represents the unloading period between preceding and subsequent actuation of SMA; *compression instance* is in which an SMA band compresses for a given period of time. A summary of our finalized set of parameters can be found in Table 1.

6.1 Compression Interval Parameters (PR1, PR2)

In edema compression treatment, fluid *backflow* can occur between compression instances. Backflow is a phenomenon where the fluid displaced from the distal location refluxes back to the distal when the pressure unloads. We aim to minimize backflow as much as possible. To examine the backflow between individual SMA bands compression and between complete sequences, we define *band interval* as an unloading period between each SMA band compression; and *sequence interval* as an unloading period between a complete activation sequence of all SMAs. Here we run a factorial test, in which we activate each of 3 SMA bands for 30 seconds, repeating 12 sequences, with/without 30-second *band interval* and 30-second *sequence interval*. The result reports that the most effective compression is when neither *band interval* nor *sequence interval* is present (Figure 6).

6.2 Compression Duration Parameter (PR3)

After eliminating *band interval* and *sequence interval*, meaning SMA bands contract continuously one after another, we examined how the duration of SMA loading affects fluid displacement. In our setup, we power each of the 3 SMA bands from 15 to 165 seconds in increments of 15 seconds (total elapsed time for 3 SMAs between 45 - 495 seconds). The result shows that powering 3 SMA bands for 105 seconds drains fluid the most (Figure 7). While 105 seconds distinctively outperformed others, this result is specific to the setup under 3 SMA bands due to the non-factorial setup.

6.3 SMA Band Number Parameter (PR4)

Our next parameter in question is whether a certain number of SMA bands transfers water more effectively than others. Building on the previous results, we start by powering 3 SMA bands for 105 seconds each without intervals between compression instances and sequences. The number of SMA increments from 3 to 10. We notice that the amount of water transferred peaks at 6 SMA bands, with the result of more than 9% of displacement (Figure 8).

6.4 Resulting Edema Mobilization Parameters

In summary, we simulated parameters that dominated fluid displacement and finalized the parameters in Table 1. The finalized parameters formed the basis of the KnitDema design and the study protocol. After we characterized the parameters, HCI researchers and rehabilitation physicians discussed the implications of the compression parameters in practice. Before we deployed the device in the user study, clinicians visited CU and tested a device programmed with the resulting compression parameters to provide assurance from a clinical perspective that the device would deliver a perceivable amount of compression without causing potential discomfort to an end user.

7 FEASIBILITY CASE STUDY

The goal of our human subject case study is to (1) understand the feasibility and safety of the device on patients with hand edema, (2) observe how participants interact with and perceive the device during the treatment, and (3) generate directions toward achieving the potential efficacy of the device. We format human subject case studies to obtain quantitative and qualitative data. To study the feasibility and potential efficacy, we introduce three phases to the study, in which we modify the compression levels from mild to moderate to high (Figure 9).

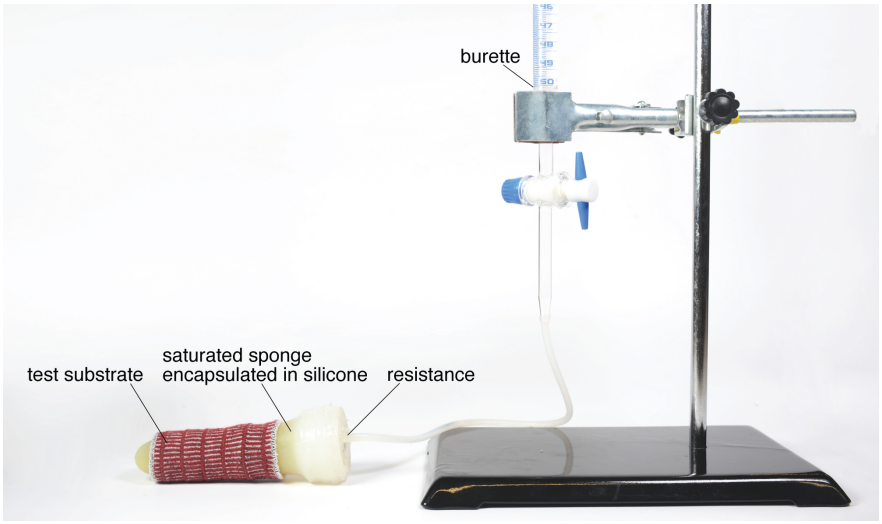

Figure 5: Setup to simulate compression parameters. Pressure applied to the mock-up finger drains the water out of the finger and into the burette.

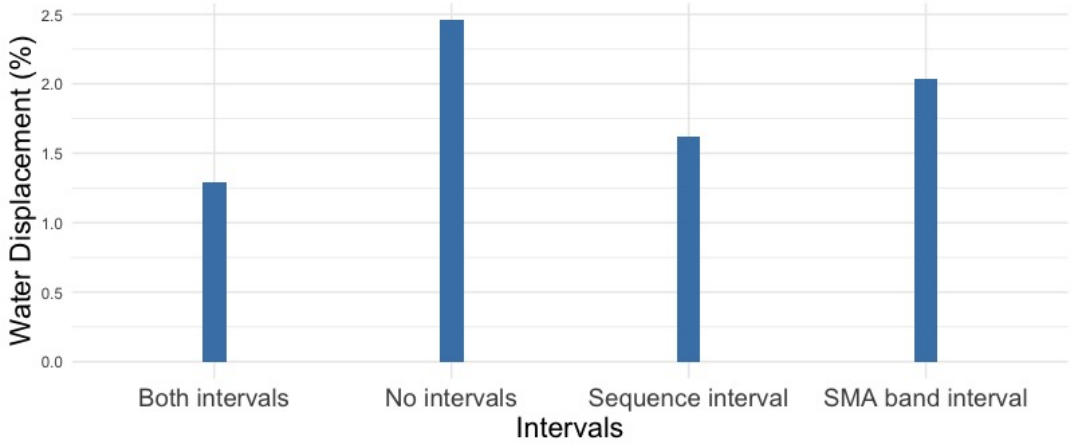

Figure 6: The result is most effective without any intervals, meaning when SMA applies pressure incessantly.

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

Table 1: Finalized parameters for active compression.

7.1 Participants

We recruit 5 hand edema patients through CMC and WCM. CMC is a regional rehabilitation clinic that offers hand therapy and lymphedema management programs. WCM is a medical institution with a rehabilitation outpatient clinic that provides physical and occupational therapy, where therapists see patients with various diagnoses, including stroke and brain and spinal cord injury. The ages of the participants range between 39 to 69, and their primary method of therapy included MEM by therapists. While some receive care more frequently than others, the maximum frequency is usually capped at twice a week. We recruit patients with various diagnoses after the screening process; all patients present with one or more swollen fingers, excluding the thumb (Table 3). The participants are not randomly assigned or stratified to the compression levels. Instead, participants first test the lowest level of compression, after which physicians determine the level of compression increments based on the patient's edema condition for safety considerations.

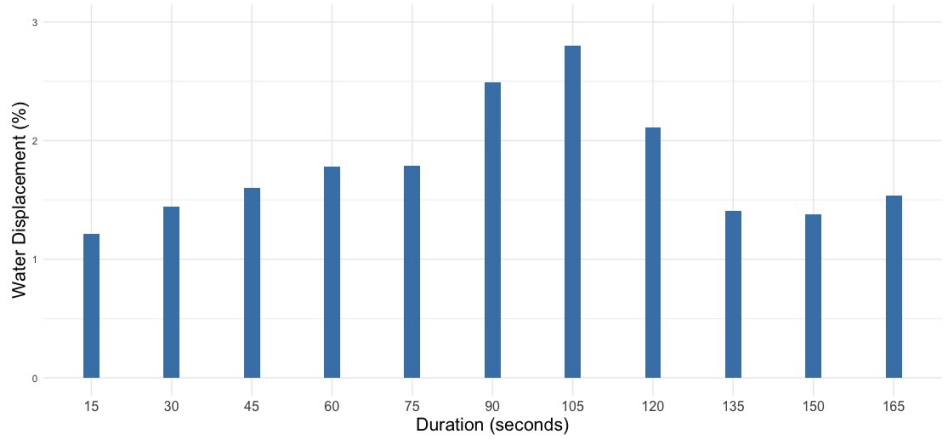

Figure 7: Influence of the duration of each SMA compression on water displacement. Three SMA bands compressed the finger prototype from 15 seconds to 165 seconds each. 105 seconds of compression mobilized 2.8% of water.

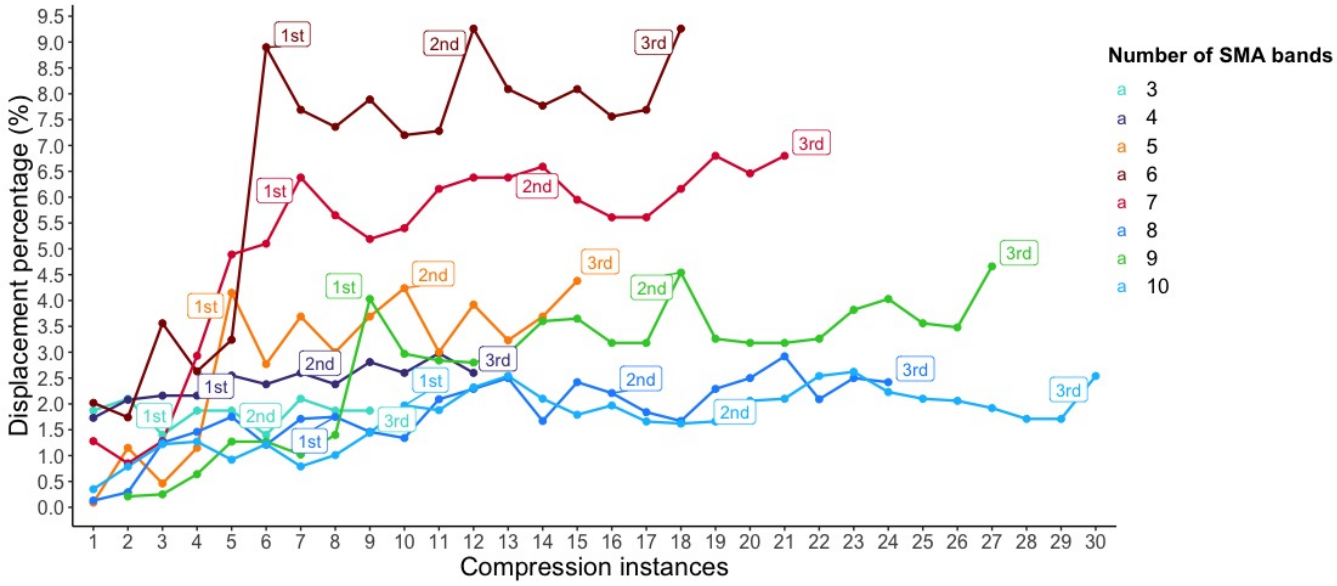

Figure 8: Simulation of the impact of SMA number on water displacement. The number of SMA bands in one substrate varied from 3 to 10, as labeled in the legend. All SMA bands ran their course three times, thus resulting in different numbers of compression instances in total. For instance, 7 SMA bands would result in 21 instances in total by the end of the operation; 5 SMA bands, 15 instances. The labels denote the end of each sequence (e.g., *1st* denotes *the end of 1st sequence*). When six SMA bands ran the full three sequences, they displaced the most fluid, more than 9% (see label *3rd* of line *6*).

7.2 Apparatus

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

pre-study survey: (1) length of the index finger, (2) circumference of $\frac{1}{3}$ distal to the base of the finger, (3) circumference of $\frac{2}{3}$ distal to the base of the finger, (4) circumference of the base of the finger, (5) circumference running from the thumb MCP to the pinky MCP, and (6) circumference of the wrist.

7.3 User Study Protocol

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

Pre-Study Survey (10 minutes). We conduct a remote pre-study survey 1-2 weeks prior to the intervention. Here we ask patient's demographic information, the standard of care, and the measurements of the affected hand (Section 7.2). We start customizing KnitDema devices based on anthropometric measurements.

Pre/Post Intervention Measurements (30 minutes each). To assess the influence of the intervention, we conduct three measurements on the affected hand before and after the intervention. The pre-intervention measurements represent the baseline, for which we measure finger volume, finger circumference, and range of motion (Figure 10). To maintain consistency, all measurements are repeated 5 times by an observer [13, 14, 38] while the order of measurements is randomized.

- **Volume Measurement**: this method quantifies the volume of the affected finger by submerging it into a tank filled with water and measuring the weight of water displaced from the tank. We mark the base of the finger and align the water surface to the mark for consistency. To carry out the accurate volumetric measurement, we custom design a 3D printed volumeter that can accommodate the web space between the index and middle finger and has a fixture inside to guide the position of the finger as it submerges (Figure 10 (a)).
- **Circumference Measurement**: we measure the circumferences of the distal interphalangeal joint (DIP), proximal interphalangeal joint (PIP), and the base. We also leave marks on the joints for consistent measurements. We repeat this measurement 5 times for each joint (Figure 10 (b)).
- **Range of Motion (ROM)**: We measure the flexion of PIP. We ask participants to perform two motions: (1) straighten the finger, and (2) flex the finger as much as possible. We repeat the motions 5 times while recording them. We use a computer goniometer to obtain angles from the videos. We measure the internal angle of the DIP - PIP - MCP (metacarpophalangeal) joint (Figure 10 (c)).

Intervention (60 minutes). We model the duration of the intervention after one-hour regular therapy sessions participants receive. As the intervention begins, we take pictures of the hand as a comparison point (Figure 11). Participants wear the device on their own. We ask participants to position their hands on the desk slightly below the heart level. Once they don the device, the device exerts 105-second pressure on each of the 6 SMA bands for 5 sequences, totaling 52 minutes and 30 seconds ($105 * 6 * 5$). This duration of the intervention was determined by therapists and rehabilitation physicians on the team in consideration of MEM therapy duration in clinics, which is typically under an hour, without breaking up the compression sequence. Upon the completion of the intervention, participants take off the device, and we take pictures of the hand to compare the hand visually.

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

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

7.4 Analysis

We analyze intra-rater reliability to take into account the multiple measurements (5 times each for the three measurements) carried out by a single observer (Table. 4). For the intra-rater reliability, we use the intra-class correlation coefficient (ICC) in R [51]. We take into account the non-independency of data across participants through the linear mixed effects model [27, 64] and *lme4* [4]. Through visual inspection, we confirm normal distribution and constant variance of residuals for all three datasets: *volume*, *circumference*, and *ROM (range of motion)*. In analyzing *circumference*, we anticipate three random effects: (1) **participants**, (2) the *interaction* between **participants** and **measurement times**, and (3) the *interaction* among **participants**, **measurement times**, and **finger joints**. We anticipate random effects of two factors for the rest of the measurements: (1) **participants**, and (2) the *interaction* between **participants** and **measurement times**.

Audio recordings of the semi-structured interviews are manually transcribed to identify salient themes. All qualitative data undergo iterative coding, which is conducted independently by two experienced researchers. We use codes with a reasonable degree of agreement among the coders to identify salient themes based on thematic analysis [8].

7.5 Results

Here we present results from the case study. For the case study, we report ICC scores, 95% confidence intervals for pre-measurements (baseline) and post-measurements (Table 4), significant outcomes, and descriptive graphs.

Volume Measurement. Linear mixed effects model reveals no significant changes before and after the intervention. In the descriptive data, a decrease in the volume is deemed favorable as it indicates edema drained. The red lines are indicative of an increase in the finger volume; the green lines represent a decrease in the finger volume. In percentage, the finger volume changes before and after intervention by +4.3%, +1.7%, -2.7%, -10.3%, and -3% for the respective participants. P4 demonstrates the largest decrease in the volume. What is notable in the volume measurement is that the participants in moderate and strong compression levels show a favorable amount of reduction in swelling (Figure 12).

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

Table 2: Specs of devices customized for patients.

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

Table 3: Participant information gathered through a pre-study survey. MEM: manual edema mobilization by therapists; IPC: intermittent pneumatic compression device; OT: occupational therapy.

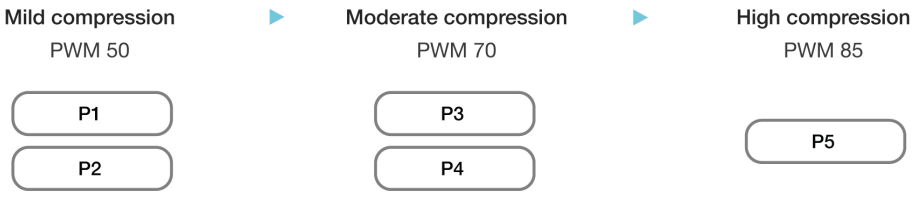

Figure 9: User study timeline and patient assignment to compression levels. Pulse width modulation (PWM) determines the voltage's duty cycle and the compression's intensity.

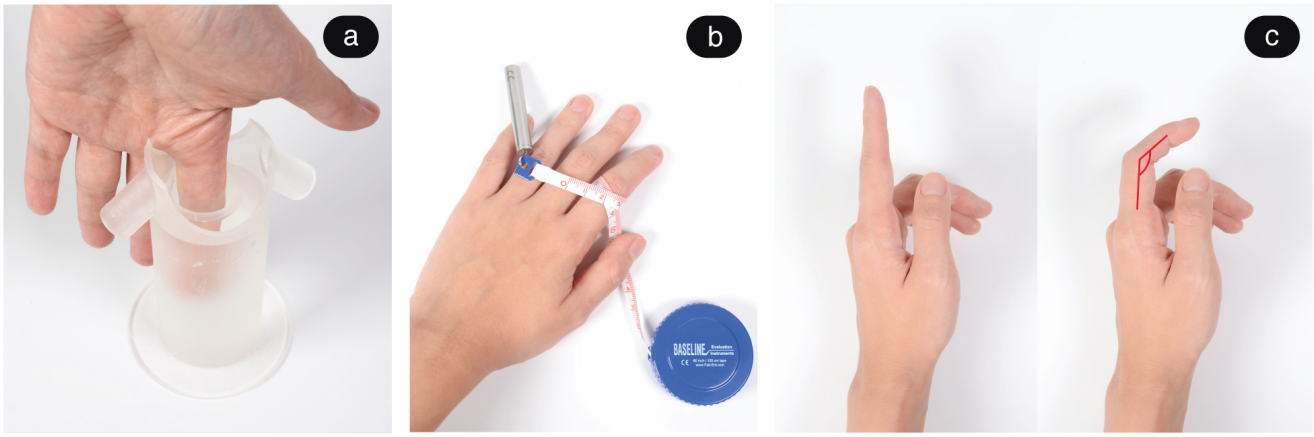

Figure 10: (a) volume measurement, (b) circumference measurement, and (c) range of motion (ROM). ROM measures the internal angle of flexion.

Circumference. The model analyzes that the differences in the circumferences across DIP, PIP, and the base joints are significant (p-value $< .001$). However, we fail to observe significant changes in the measurement before and after the intervention. As for descriptive data, we consider the decrease in the circumference a sign of favorable results. As before, the green lines indicate a decrease in

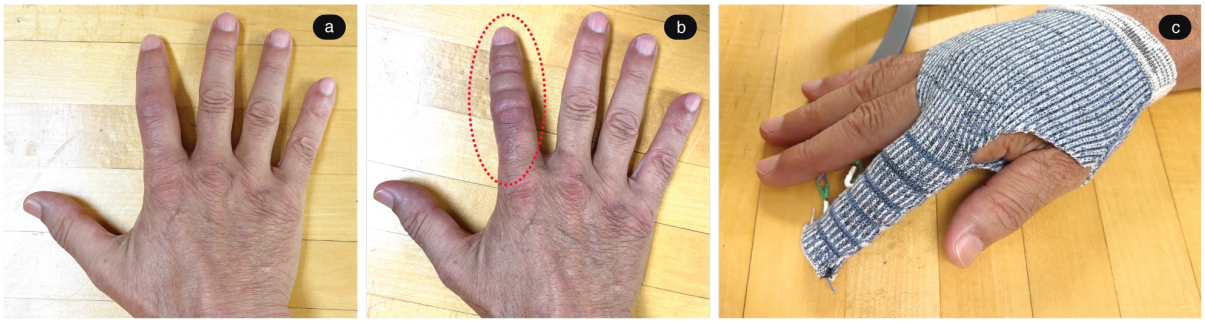

Figure 11: Photographs of a participant's hand before (a), and after (b), the intervention (c). Marks from intervention indicate that the pressure is palpable and the device fits the finger snugly.

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

Table 4: Intra-rater reliability of measurements and CIs. ICC score close to 1 indicates high similarity between measurements.

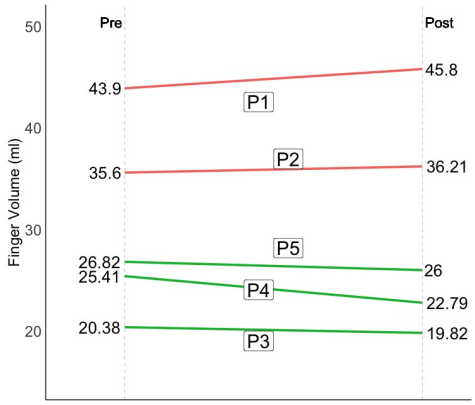

Figure 12: Changes in the finger volume before and after the intervention, labeled by participant code. Red indicates an increase, and green indicates a decrease in the volume.

the measurement while the red represents an increase in circumference. P5 shows noticeable decrease of 4.1% in circumference on average, followed by P4 (-1.9%), P1 (-1.1%), P3 (-0.3%), and P1 (1.1%). As for the circumferences of the joints, DIP changes by -2.2%, PIP -1.5%, and base -0.5%, showing a diminishing tendency in general from distal to proximal (Figure 13).

Range of Motion. Literature suggests that the success of manual edema mobilization is correlated with an increase in the range of motion [50]. Our analysis shows no significant changes in ROM before and after the intervention. Descriptive data informs that the green lines indicate a decrease in the flexion angle, which is deemed favorable, while the red lines indicate an increase in the range of motion. ROM is where we observe a high level of variance among the patients due to underlying medical conditions, as some participants who have their mobility compromised have difficulty flexing their fingers. Participants, on average, show a decrease of 1.7% flexion angle after the intervention, which is deemed favorable (Figure 14).

Post-Study Survey and Semi-Structured Interview Findings. The post-study survey revealed insights into how participants interacted with the device and formed the foundation of our semi-structured interview. In this survey, we asked eight 7-point Likert scale questions on the themes of **wearability**, **sensation**, and **comparison with the standard of care**. This was followed by a

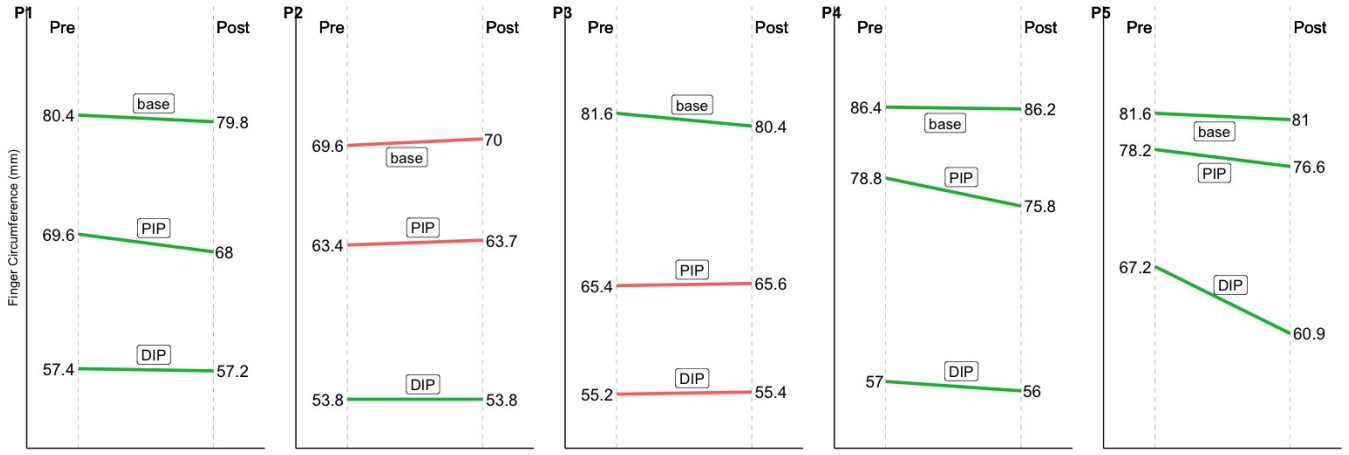

Figure 13: Changes in the circumference of the DIP, PIP, and base, before and after the intervention. Red indicates an increase, and green indicates a decrease in the measurement.

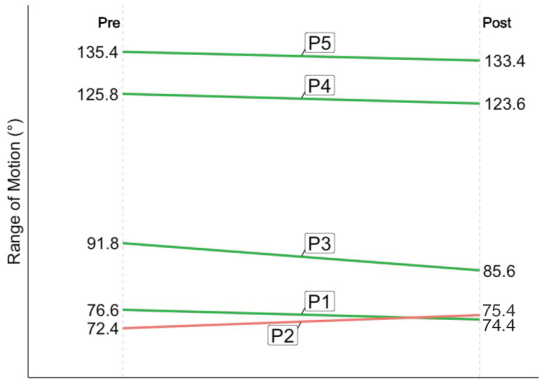

Figure 14: Changes in the range of motion in degrees (°) before and after the intervention, labeled by participant code. Red indicates an increase, and green indicates a decrease in the internal angle of flexion.

semi-structured interview where we expanded on these themes for each individual's experience.

- **Wearability**: On the Likert scale (1: extremely uncomfortable, 7: extremely comfortable), participants rated the donning and doffing process with a median score of 6. There was consensus that the knit substrate made donning and doffing of the device comfortable. This comfort was also observed during the intervention, obtaining a median score of 6 (1: extremely uncomfortable, 7: extremely comfortable). Participants pointed out that "It was very, very light. I couldn't even tell if it was on. It was comfortable, but it didn't over squeeze." (P1). The knit's materiality was also positively associated with wearability: "It wasn't sticky on the skin" (P1). Participants also reported that they became accustomed to the device throughout the intervention process (median score 6. 1: strongly disagree, 7: strongly agree). On the other hand, participants attributed most of the factors that constrained wearability to the exposed wires in the current prototype and the 3D-printed enclosure and expressed a desire to integrate everything into the fabric glove. Because the SMA springs were connected to the enclosure, some pointed out that the wires could catch onto objects and might get in the way. They suggested we integrate the wires into the glove. "I'd tuck them (wires), so you didn't have to have them around." (P3). "Only issue was when the wires are coming out." (P5). P5 mentioned that the hardware could also be integrated into the fabric: "you could put that (enclosure) right into the glove." (P5)
- **Sensation of compression and heat**: Unlike the overwhelming consensus towards wearability, participants varied on their perception of compression. On the question asking if they perceived compression evenly across the finger, they rated a median score of 2 (1: highly clustered and 7: highly distributed). During the interview, it was plain to see that most participants did not perceive pressure evenly across the finger due to various reasons. While P3 noted the compression was felt "towards the finger base," for P2 and P4, the compression was more vivid on the joints. P2 mentioned experiencing compression "towards bony rather than

fatty areas." P4 mentioned mostly feeling "strain on the joint." On the other hand, P5 perceived compression steadily and evenly across the length of the finger. Rehabilitation physicians on our research team reflected that this might be due to different etiologies impacting individual tolerances toward pressure. Several participants (P2, P3, P5) perceived the sequential compression to be moving in a certain direction. Besides compression, another sensation was slight heat. However, it did not cause discomfort. All participants experienced a slight degree of heating regardless of compression levels: "definitely had the warmth." (P3), "there was heat besides compression." (P4), and "here is slightly warm." (P5). Other described sensory stimuli that accompanied compression were "a little twinge" (P2) and "pulsing" (P5). Regardless of the experienced sensation, it did not cause discomfort to the level requiring a change in posture during wear (median: 7, 1: change posture all the time, 7: not at all).

- **Comparison to the standard of care**: Participants were neutral on the appearance of the device (median: 4, 1: strongly disagree, 7: strongly agree). However, they found the device barely awkward despite the unconventional form factor (median: 2, 1: strongly disagree, 7: strongly agree). Participants seemed to enjoy silent actuation compared to the pneumatic compression counterparts: "(the device) doesn't make noise. It's very quiet." (P1). They often preferred the reduced bulkiness over the pneumatic compression device: "it's less bulky." (P1). Participants who received manual edema mobilization as primary treatment noted that the device could provide equal compression across the perimeter. They perceived compression "equally around the finger." (P2), while therapists would massage less evenly with their fingers: "It's the thumb, index and the middle fingers, so you're not getting the whole ring whereas your device is actually working the entire ring around the finger." (P3). Participants who used compression garments commented that too much pressure would fatigue their hand, "I get totally waffly." whereas KnitDema was "soft compression" and "equally around the finger." (P2). Adding to the responses, P5, who received taping treatment, referred to the device as "steady" compression compared to taping. P5 noted that taping treatment could be "uneven" and result in cramps (P5).
- **Potential as a remote treatment device**: Participants were positive concerning KnitDema's potential as a future treatment device. Participants rated a median score of 5 regarding if they could see themselves wearing the device in their everyday lives (1: strongly disagree, 7: strongly agree). It was shared among the participants that the "full glove would be really helpful." and that "if it were portable [I would] bring it to work." (P2). Many expressed interest in using the device during sleep so the swelling would subside in the morning: "it would be absolutely wonderful if you could wear it to bed." (P3). P5 mentioned the device could offer programmability of the compression as needed, "I think the ability to program compression [is helpful] because I think it was a little too light." (P5). Many noted that they would put the device to use in during pockets of time: "lunch break" and "watching TV" (P5), or "I'd use it while reading." (P1). These responses highlighted how participants were eager to make use of scrap time for treatment to help swelling diminish. The interview also shed light on potential areas for improvement. Among the concerns was the possibility of the wires disconnecting while using it in public, "anytime you have electronics on the outside, you're gonna be afraid of, like, disconnecting." (P2).

8 DISCUSSION, LIMITATIONS, AND FUTURE WORK

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

8.1 Reflections on Co-Designing Wearable Device for Clinical Uses

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

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

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

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

8.2 Future Roadmap of KnitDema

The achievements from the feasibility study of KnitDema lay an important ground for future work. Most notably, the next iteration of the device will have improved efficacy through (1) extended coverage of the hand, (2) robust measurements, and (3) mid or long-term deployment of the device. As opposed to the current fabrication process, which is out of reach for those without expertise in computational knitting, KnitDema could lower the fabrication barrier by developing a fabrication pipeline and inviting therapists and physicians. Finally, for KnitDema to evolve into a true telehealth tool for managing edema, we plan to deploy the device in the wild and evaluate it with appropriate methods.

Improving the Efficacy of KnitDema We have identified several paths toward improving the device's efficacy. Rehab physicians pointed to the parametric approach we took in testing compression parameters, as opposed to an anthropometric approach in which one measures an individual's body landmarks (i.e., joints and fingernails) as design parameters (e.g., water displacement expressed as a function of SMA band $x$cm off from the metacarpophalangeal joint). They reflected on how the high variance of landmarks across individuals could have interfered with consistent compression. Literature also suggests that interstitial edema (i.e., hand edema) should be distinguished from the swelling within a joint, namely effusion [20]. Ways to improve the efficacy could otherwise include adopting more rigorous approaches in the measurements. For instance, working with more raters could enhance the reliability across the measurements. Given that the volume measurement was contingent on one hand, an alternative measurement could compare the volumetric ratio of the affected hand to the unaffected hand as demonstrated in [7]. Lastly, other methods to achieve successful results could include considering other parameters for active compression. These parameters could include: (1) irregularly dispersed SMA bands where the bands are dense on the fleshy area and sparse around joints, (2) overlapping compression duration between the bands, and (3) increments in the duration of compression throughout each cycle. Additionally, physicians highlighted the importance of diversifying stimulation methods based on etiology. Depending on the etiology, alternative stimulation/activation paradigms could be trialed to improve efficacy. For example, a patient with lymphedema may have different drainage physiology than someone with swelling following a traumatic injury like a wrist fracture.

Toward a Full Hand Prototype with Robust Performance and Accessibility As the first step towards a personalized rehabilitation device, we centered on designing and testing SMA-driven edema mobilization for a single finger. During the study, participants expressed how the compliant nature of KnitDema was desirable as the device fits the hand and fingers snugly. This positive feedback could be amplified as we advance the coverage of the fingers to the full hand. Moving to a full-hand device while improving its efficacy could help us see the qualitative study's statistical significance and positive feedback. On the performance front, future work to encompass the full hand could include investigating fluid dynamics between the palm and fingers. The reflux of fluid back to the fingers as the palm is being compressed could be alleviated by adjusting compression parameters. In addition, physicians and therapists highlighted that KnitDema should provide a more clinician-friendly interface to lower the barrier of programming and tuning compression parameters. In addition to a full-hand device, we plan to advance the hardware for more interaction such that therapists could easily program parameters for remote use. This will allow us to run human subject studies at scale and, in turn, strengthen the clinical feasibility and efficacy of KnitDema.

Long-Term and In-The-Wild Deployment Participants were enthusiastic about using the device in residential settings. They highlighted the device's portability and that KnitDema could become a readily available treatment not tethered to clinics. Participants mentioned experiencing the "ebb and flow" of symptoms throughout the day, again emphasizing the need for more readily available treatment options. Another aspect that made participants passionate about the device in residential settings was the programmability of compression; participants appreciated the ability to modify the compression parameters to their needs. To allow KnitDema to become a fully-equipped at-home device, we plan to run in-the-wild user studies in which participants are expected to take the device home and evaluate the device through event-based reports.

Inclusive and Comprehensive Fabrication Pipeline While therapists and physicians showed keen interest in participating in the designing process of the device, the current process required familiarity with the knitting software and setup of the machine. An accessible pipeline that implements a web-based knit design tool, compression simulator, and GUI could help a broader group of people simulate and fabricate devices. A computational design pipeline holds great promise for therapists and physicians in particular, as they could adjust the device as they see fit to specific diagnoses and individual sensory attributes. These modifications could improve long-term adherence by providing hyper-personalization of psychophysical scaling alongside body geometry.

9 CONCLUSION

We present the design and development of KnitDema, a digitally knit robotic textile that is individually programmable for sequential compression across finger phalanges for mobilizing hand edema. With rehabilitation physicians and therapists, we adopt a co-design method throughout the design, development, and implementation phases of the project. We simulate KnitDema's compression ability and test parameters that determine the effectiveness of active compression. Drawing from the results, we design the device with

parameters that effectively shunted fluid. We conduct a case study of KnitDema with 5 persons with edematous hands to obtain a qualitative and quantitative understanding of device feasibility. Measurements of volume, circumference, and range of motion demonstrate the feasibility and potential efficacy of KnitDema. The semi-structured interviews highlight the wearability of the device, participants' perceptions of compression, how the device compares to other standards of care, and KnitDema's prospects as a personalized device for treating hand edema. This project sheds light on the potential of using the under-explored advantages of robotic textiles as a *personalized* rehabilitation tool that is inexpensive to manufacture and comfortable to wear.

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