Compressables: A Haptic Prototyping Toolkit for Wearable Compression-based Interfaces

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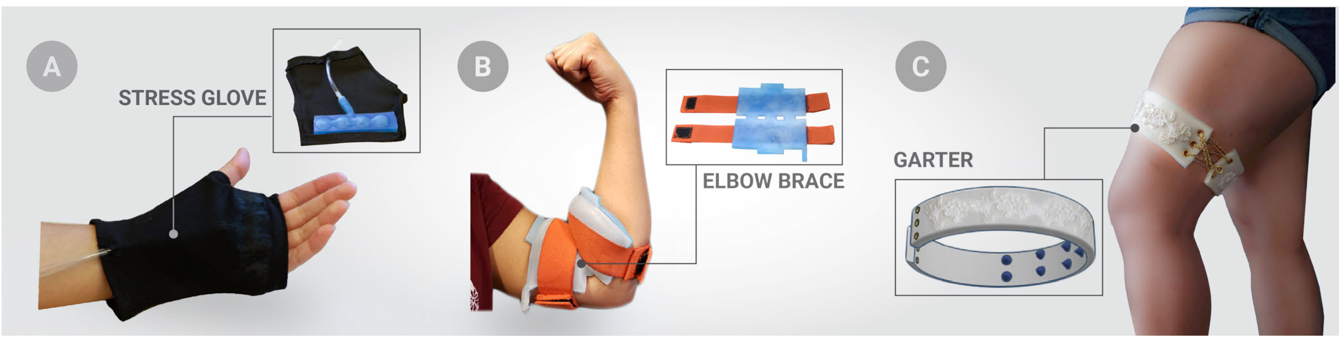

Figure 1: Compressables. A: An air bladder fused inside a fingerless glove inflates to provide stress-ball like interaction; B: An air bladder is fused with elastic straps to wrap around the elbow joint to track reps during exercise; C: An air bladder fused with lace and studded with tacks is wrapped around the thigh to provide an immersive gaming experience.

ABSTRACT

Compression-based haptic feedback has been used in wearables to issue notifications, provide therapeutic effects, and create immersive storytelling environments. Such worn devices are well studied on the wrists, arms, and head, however, many unconventional yet context-rich areas of the body remain underexplored. Current haptic prototyping techniques have large instrumentation costs, requiring the design of bespoke embedded devices that do not have the flexibility to be applied to other body sites. In this work, we introduce an open-source prototyping toolkit for designing, fabricating, and programming wearable compression-based interfaces, or *compressables*. Our approach uses a lost-PVA technique for making custom inflatable silicone bladders, an off-the-shelf pneumatics controller, and a mobile app to explore and tune haptic interactions through sketch gestures. We validate the toolkit's open-endedness through a user study and heuristic evaluation. We use exemplar artifacts to annotate the design space of compressables and discuss opportunities to further expand haptic expression on the body.

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CCS CONCEPTS

• **Human-centered computing** → **User interface toolkits**; **Haptic devices**.

KEYWORDS

wearables, compression, toolkits, haptics

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1 INTRODUCTION

Designers of on-body wearables are turning towards incorporating forms of haptic feedback to enable rich, embodied interactions. Complementing traditional visual or auditory feedback, haptics allow designers to develop immersive experiences in augmented and virtual reality [37], to offset cognitive load and attention [27], and to engage more of a learner's body in sensemaking [4]. Such feedback mechanisms have expanded to include vibrotactile [13], compression [25], thermal [17], and pain sensations [35]. Despite the value of haptic feedback in interaction design, understanding the relationship between stimulus, perception, and interpretation of haptic expressions is heavily dependent on the site of the body in which it occurs. A gentle buzz on the wrist can be a blaring

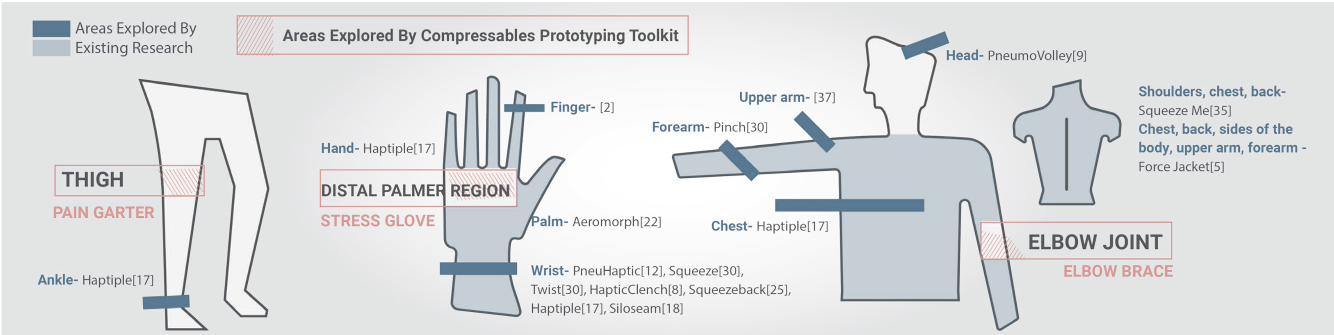


Figure 2: A comparison of sites of compression-based haptic wearables created using existing toolkits and the Compressables Prototyping Toolkit.

signal on the forehead. While some studies aim to characterize the different psychophysics of the body [5], we aim to complement this endeavor and enable designers to design, implement, tune, and study haptic feedback across all sites of the body to explore the unconventional, unexpected, curious, and taboo.

We introduce our Compressables Prototyping Toolkit (CPT), an open-ended haptic prototyping toolkit for designing, fabricating, and programming compression-based haptic interactions[1]. Our toolkit uses an off-the-shelf pneumatics controller[2] to wirelessly control bespoke and inflatable silicone bladders configured for different regions of the body. The bladder fabrication process is highly versatile and builds on our Siloseam [18] work; we demonstrate how this process can be used to create various form factors to explore compression-based interaction on targeted regions of the hand, limbs, and joints (Figure 1). Using three exemplars design, we demonstrate our toolkit's flexibility in exploring different haptic sensations across a wide range of scenarios. We conduct a user study with 6 participants to demonstrate usability and open-endness, complemented with a heuristic evaluation using Olsen's [20], guidelines for toolkit evaluation and comparison.

In this paper, we first position our prototyping toolkit against existing wearable and haptic toolkits and walkthrough the process of designing a compressable. We then motivate our system design choices and describe our open-source implementation. We then discuss the CPT toolkit's evaluation results against haptic design principles and tie our findings to the larger research initiatives for expanding haptic expression on the body.

2 RELATED WORK

Recent advancements in hardware and wearables prototyping are expanding the sites where we encounter haptic feedback. We review interactive devices, systems, and toolkits for generating haptic sensations or supporting haptic design, as well as compression-specific wearable devices. We annotate the sites of worn compression-based haptic devices in Figure 2.

[1]The sensation of compression-based haptics is similar to an inflatable blood pressure measuring cuff

[2]Programmable-Air https://www.programmableair.com/

2.1 Haptics Prototyping Toolkits

Haptics prototyping toolkits help HCI researchers develop novel haptic interactions and minimize instrumentation costs. Some prototyping toolkits incorporate off-the-shelf components to reduce hardware implementation. The *Let Your Body Move* toolkit simplified prototyping of wearable and mobile EMS devices by using off-the-shelf Electrical Muscle Stimulation (EMS) devices [24]. *Haptic Collar* used off-the-shelf vibrotactile actuators on a neck worn band for eyes-free navigation [28]. However, combining these components into an interactive system remains a challenge, especially when considering how these devices intercommunicate with each other. Our toolkit uses an off-the-shelf pneumatic controller to provide compression feedback and a communication framework that is extendable to most WiFi-enabled devices.

A graphical user interface often supports a designer in rapid prototyping and sensemaking activities, but challenges remain in portraying non-visual qualities like haptics. Pohl et al. [26] designed a touch toolkit where interactive tactile surfaces changed their tactile properties based on direct manipulation. The SoD Toolkit [29] provided a visualizer for monitoring entities within their environment, prototyping, and calibration. Our toolkit provides a real-time visual sensor stream and supports control of haptic expression through gestural interactions.

Many toolkits make it possible for simplified interaction design by abstracting hardware and software technicalities. Ledo et al.'s [15] HapticTouch toolkit simplified the development of haptic-enabled applications for surface-based interfaces through an application programming interface (API). WoodenHaptics [6] encapsulated mechanical and electrical technical details to allow designers to design a fully working spatial haptic interface. The *Pneuduino* toolkit simplified complex behavior programming by providing an Arduino library to support rapid interaction design of inflatables [41]. Similarly, our toolkit provides a mobile application to live program pneumatic control and experientially explore different haptic sensations.

Open-ended haptic design is favored by architectures that allow relevant sensors and devices to be seamlessly integrated into the system. Pfeiffer et al. [24] used wireless communication over Bluetooth Low Energy to enable easy connection to different mobile and wearable devices to aid in rapid interaction design. Seyed et al.'s [29] toolkit provided a client-server architecture to easily integrate devices using websockets and provide multi-platform, web-based support to help researchers design applications and interactions in ubiquitous spatially-aware environments. Our toolkit also uses Websocket communication to overcome the limitation of a single control device and allow multiple mobile phones to control the device or view live data streams simultaneously to support collaborative haptic prototyping. The architecture uses an event listener model to program interactions, supporting integration with existing interaction design programming practices.

2.2 Compression-Based Haptic Wearables

Wearable haptic tools create opportunities to study haptic feedback on the body and develop novel applications of haptic sensations. Researchers have found that haptic feedback can be used to mimic human touch [30] and used this property to develop tools to assist in therapy and meditation [35]. Haptic wearables create a sense of connectedness with the environment which is why it has been extensively used to create immersive virtual reality applications [5, 9], amplify creative experiences [37], and aid in learning [33, 38, 40]. Haptic wearables have also been used to convey spatial patterns and gradual progression of activities [8].

While compression-based haptics has been used to provide haptic sensation to the body, several hardware and software challenges remain. Delazio et al. [5] used pneumatically actuated airbags in Force Jacket which provided directed force and high frequency vibration on the upper body for virtual reality applications, but the system became very bulky due to the large number of solenoid valves needed. PneuHaptic [12] consisted of pneumatically actuated silicone air chambers attached to two air compressors, three solenoid valves and power supplies on a wristband. The mechanism limited the number of air chambers that could be placed on the wrist, lowering the spatial resolution desired by He et al. [12]. The complexity, bulkiness, and instrumentation costs of pneumatic mechanisms limit the areas of the body where compression feedback can be provided [25]. In many cases, the circuitry required is integrated into the wearable and does not translate to a different form factor without additional costs [12, 37].

Shape-Memory Alloys (SMAs) has also been used for their lightweight, flexible and silent properties [2, 8, 10, 30]. However, SMAs require significant power to drive these components and additional components for heat insulation, increasing design cost. Our toolkit uses pneumatics to curb some of the drawbacks of SMA mechanisms and allows fabrication of wearables that are standalone, connected to an external pneumatic controller with quick-release airtube connectors, eliminating the need to redesign the controller for different form factors. Decoupled and distanced from the controller, the worn artifact does not inhibit motion or require significant integration efforts.

2.3 Fabrication Approaches

Pneumatic-based compression feedback often uses airtight structures, fabricated using a variety of techniques, to selectively inflate and deflate. Lu et al. used a CNC-controlled heater to fuse thin-films together at scales suitable for wearable application[16]. Vazquez et al. [36] 3D printed pneumatic control structures using VeroClear

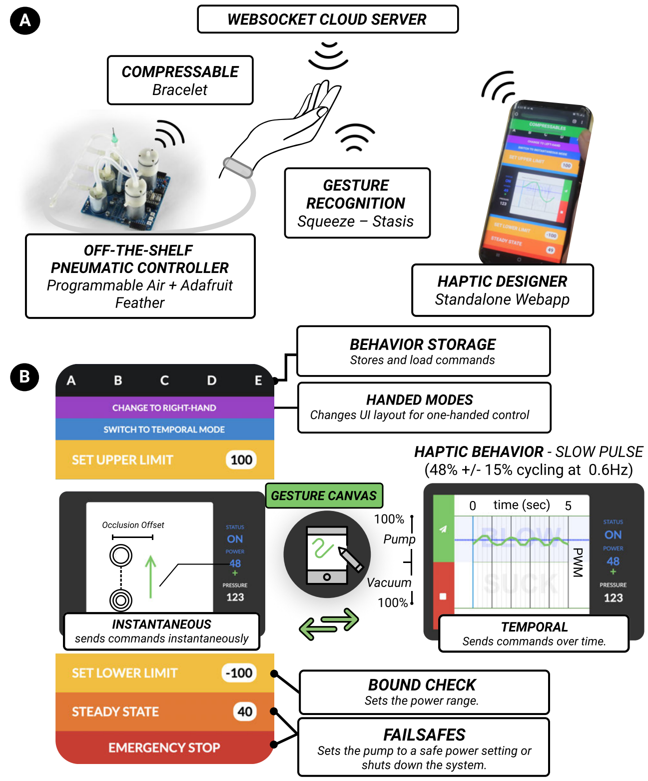


Figure 3: Compressables Prototyping Toolkit. A: An off-the-shelf pneumatic controller is attached to a compressable bracelet using an air tube; all components intercommunicate using a websocket-based IoT server; B: A haptic design tool allows users to sketch compression-based behaviors and control the worn compressable.

(rigid material) and TangoPlus (elastic material). Yao et al. [41] sandwiched crease paper between two layers of silicone, one of which is embedded with an airbag and connected to a pneumatic controller, to achieve controlled bending and curling of the inflatable. Moradi et al. [18] described a lost-PVA technique for creating silicone bladders using 3D-printed molds. We leverage this technique in our toolkit, but are able to create form factors that are larger than the printbed size of 3D printers. Different strategies have been proposed for integrating pneumatic-based control with these airtight structures to expand the type of interactions that can be achieved. Yang et al. [39] incorporated silicone airtight structures with custom 3D printed Lego bricks to create a snap-fit mechanism to connect to an external control system. Ghosal et al. [7] daisy-chained several pneumatic control boards to operate multiple balloons at the same time. Tejada et al. [32] used holes in a tangible air-filled object to observe the changes in pressure inside the model when the holes are touched. In wearables, hiding the compression mechanism behind a clothing article such as a vest provides the user privacy and allows for development of sensitive interactions [21, 22, 35]. Other wearables that lack privacy may be more useful in studies and workshops rather than day-to-day activities [37]. Our toolkit provides fixturing methods inspired from traditional clothing and jewelry for open-ended exploration of form factors and interactions.

Our related works suggest that despite the progress in compression feedback mechanisms, there lacks a toolkit that supports experiential design of haptic behaviors across multiple form factors. In the following section, we describe our design principles and motivate the design rationale behind our toolkit.

3 TOOLKIT DESIGN

We use the term *compressables* to describe a class of wearables that either generates a compressive force or senses compressive forces from external stimuli. Compressables developed with our toolkit consist of an inflatable *bladder* that has been integrated onto a wearable *form factor* which holds and constrains the bladder against the skin. This bladder is then controlled by a pneumatics *controller* to provide a user with both input capabilities and feedback (Figure 3A). This compression feedback can range from feeling comfortable to feeling immobile depending on where the feedback is applied [25].

Designing a compressable has significant instrumentation costs, however these barriers are lowering with off-the-shelf pneumatic controllers and rapid prototyping techniques for creating custom airtight structures [7, 16, 18, 32, 36, 39, 41]. Integrating these two components into a wearable form factor faces challenges from traditional upload-and-compile hardware prototyping workflows that limit iterative haptic interaction design. This is especially crucial to the experiential and exploratory nature of haptics design, the range of haptic sensitivity and perception of different sites of the body, and the context-specific interpretations of haptic stimuli.

Based on principles in haptic toolkits [6, 15, 24, 28, 29], wearable frameworks [5, 12, 25], and personal experience with designing wearable devices, we reflect on the affordances and resistances in haptic and wearables design to determine the limitations of existing systems and present the following design principles for compression-based feedback prototyping:

- *Body versatility* - Haptic sensitivity on the body changes both in terms of context and concentration of haptic receptors. A stroking sensation on the wrist feels different from a stroking sensation on the forehead. The toolkit should support designs across all body parts and promote open-ended exploration of haptic sensations.
- *Wearability* The toolkit should promote the wearability by, at minimum, ensuring that the wearable follows the natural shape of the body part in which it is worn, minimizing weight, maintaining freedom of movement unless immobility is the intention of the interaction, promoting comfort and ease-of-wear, and easily adapting to the shape and size of the user's body [23]. It is important that the pneumatics controller reduce tethering, minimize adding significant weight, or otherwise limit the mobility of the body.
- *Opportunistic and on-the-fly interaction design* - The toolkit should allow quick reprogramming for iterative prototyping and adjust for context-of-use.

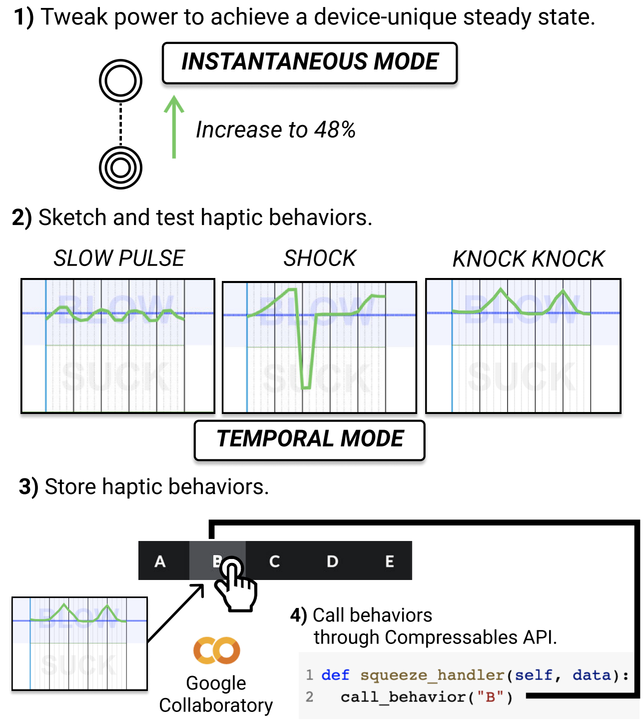


Figure 4: Haptic Design Walkthrough. 1: A user can alter the power supplied to the pneumatic pump or vacuum instantaneously through a drag-and-release gesture; 2: using a sketching gesture, a user can specify power supplied over time to create different haptic expressions; 3 and 4: Sketched behaviors can be stored and recalled within the app or called directly by applications connected to the Compressables websocket server.

4 WALKTHROUGH

To operationalize and ground how a compressable is made using our prototyping toolkit, we describe the creation of a compressable glove (Figure 5). Prescilla is an interaction designer who wants to design a therapeutic intervention for a client.

Form Factor Exploration Prescilla downloads a set of **form factor** design files to create silicone bladders (circular-form, ring-form, and strap-form) to explore different haptic sensations on the body. She holds them against different parts of her hand with a repositionable velcro strap and inflates the bladders with a hand bulb. She discovers that the wrist (a prime location for a wearable) has underwhelming haptic sensitivity; in contrast, placing the modular bladder on the distal palmar region, or the area between the fingers and the palm, creates a curious and unique haptic sensation. She modifies the design files to create a bladder to target this specific region.

Form Factor Refinement Prescilla looks through the toolkit's annotated set of **fixturing methods**, or techniques for combining silicone with other materials more amenable to creating wearable form factors. She sees that *fabric fusion*, or using uncured silicone to fuse with woven fabric, can be used to connect the bladder to

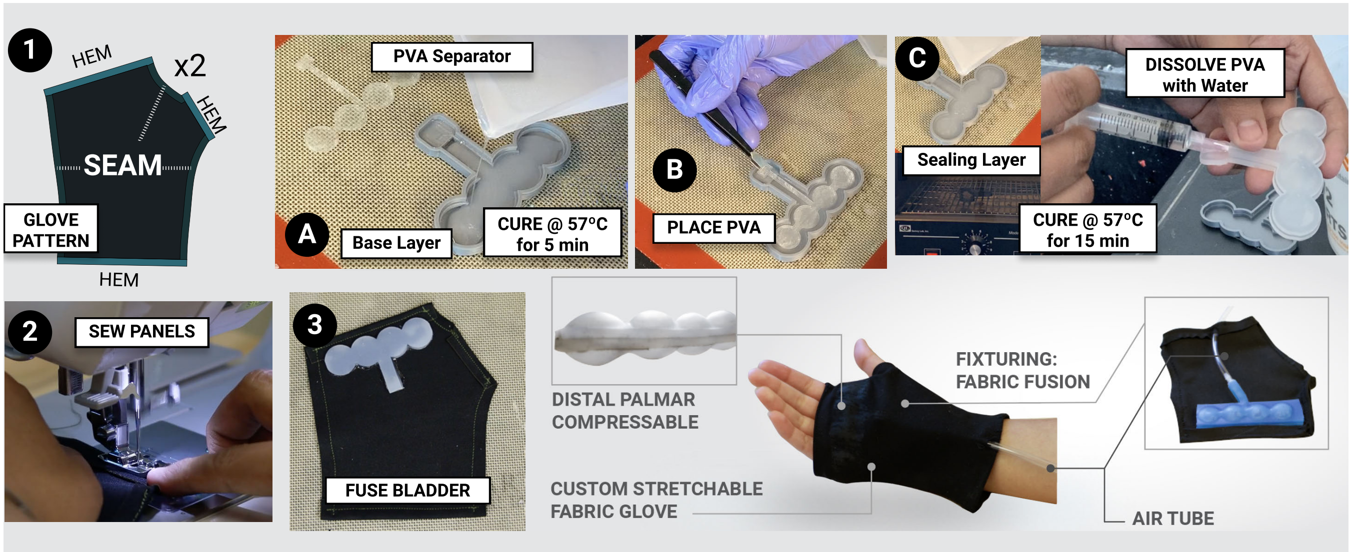


Figure 5: The Making of a Stress Glove. 1: A glove pattern is designed and laser-cut from fabric; 2: The laser-cut pieces are sewn together to form a fingerless glove; A, B and C: Silicone bladder fabrication (Section 5.1); 3: The bladder is fused to the glove using silicone as glue; Bottom right shows the final compressable.

cloth. Using her textile forming skills, she creates a fingerless glove form factor and fuses the silicone bladder on the part of the glove that makes contact with her hand's distal palmar region as shown in Figure 5. She connects the glove to an airtube and the toolkit's pneumatic controller.

Haptic Interaction Design Depicted in Figure 4, Prescilla then uses the toolkit's **haptic design tool** to first set a steady state by tweaking the inflation rates. She **sets limits** to prevent the bladder from rupturing, deflating, or becoming uncomfortable. She switches to a temporal mode that allows her to **experientially sketch** different haptic behaviors on a gesture canvas by drawing different waveforms that are interpreted as pump and vaccuum power commands. Using a computational notebook, she **binds** these haptic behaviors to activate whenever a squeeze gesture is detected.

Through iteration, Prescilla observes that the slow pulse behavior feels comfortable and mimics a breathing pattern. Her final design emulates a stress ball which she achieves by toggling a slow pulse behavior to a squeeze event.

5 TOOLKIT IMPLEMENTATION

The Compressables Prototyping Toolkit[3] consists of two core components: a) a physical design and fabrication framework that describes techniques for designing a compression mechanism into a wearable form factor, and b) a haptic interaction design tool that uses a wireless communication infrastructure for iterative prototyping.

[3]All relevant source code, hardware and model files, and a step-by-step tutorial are provided as supplemental materials: https://github.com/The-Hybrid-Atelier/Compressables-Prototyping-Toolkit.

5.1 Design and Fabrication of Compressables

Our process uses inflatable silicone bladders that are held against the body using jewelry- and clothing-inspired fixturing methods to administer a compression-based force.

Air Bladder Fabrication We fabricate bladders, or airtight structures, using a soft, flexible, and skin-safe silicone rubber (EcoFlex 00-50, 980% elongation at break). The bladders are fabricated using a lost-PVA casting method developed by Moradi et al. [18], but modified to scale to larger form factors. The process involves sandwiching a dissolvable material such as 3D-printable PVA, or *separator*, between two layers of silicone. Using a 3D-printed mold, this fabrication process can be carried out in about 15 minutes resulting in a testable bladder within 30 minutes (Figure 5B). A high-level overview of the process is given below:

(1) Using an SVG editor, we design a separator with an airtube geometry (inlet) and 3D print it in PVA. For larger geometries that do not fit the printbed, the separator design is 3D printed in pieces which are then fused together with water. The SVG design is also used to generate a block mold. Molds are 3D printed or separated in lasercut layers which are then fused. Slicing and fusing molds with glue increase fabrication errors, thus lasercutting is preferred for larger forms.
(2) A silicone mixture is then degassed in a vacuum chamber (optional) and poured into the mold to form a **base layer**. We speed cure the mixture using a heatpad/incubator at 57 C (135 F) for 5 minutes.
(3) Once cured, we then **place the separator** on top of the first layer and pour a **sealing layer** of silicone and cure as before.
(4) Lastly, we **dissolve the separator** by injecting water through the inlet using a syringe. After a few minutes, the dissolved PVA can be squeezed out through the inlet and the bladder can be inflated with air.

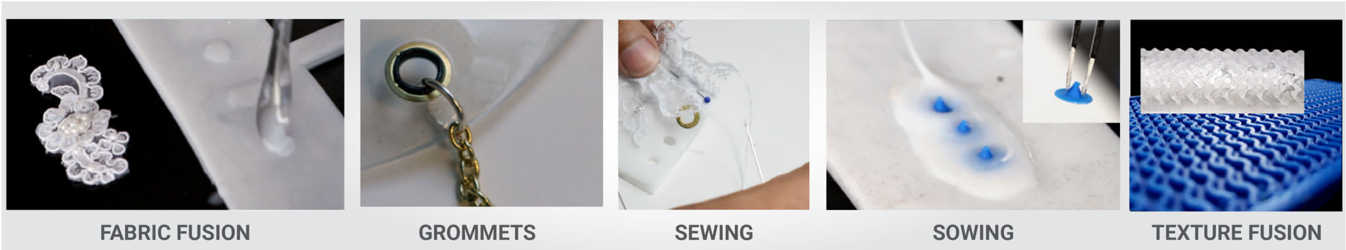


Figure 6: Five different fixturing techniques provided by Compressables Prototyping Toolkit to improve wearability.

Integrating and Fixturing Air Bladders The majority of form factor techniques used in compressables mirror those found in a blood pressure cuff – a fabric strap is used to press the bladder against the skin, and a velcro strap is used to adjust size and fit. We present five fixturing methods inspired from clothing and jewelry formgiving techniques (Figure 6); while these techniques are readily used in different practices, we unify these techniques under this toolkit to better support creating personalizable, comfortable, aesthetically pleasing, and form-fitting compressables that fit unique use cases. The fixturing methods include:

- **Fabric Fusion** While few materials stick to silicone, woven fabrics can fuse to silicone. This technique requires uncured silicone to be applied, like glue, to the silicone bladder and piece of fabric. The uncured silicone seeps through the warp and weft and cures into a fused state. Fabric fusion thus allows silicone to enter into the range of textile formgiving techniques. We fuse straps of elastic fabric (to preserve the stretchable properties of the silicone) and affix velcro to the ends of the straps. When fused to the lining of a garment, this technique allows for the bladder to be inconspicuously attached to target regions of a garment.
- **Grommeting** Metal grommets, traditionally used to reinforce textiles, can be used to interface with strand-like materials. The technique involves punching out a hole in the bladder's seam and crimping a metal grommet into place. Materials like chains, leather straps, and shoe laces can be used to fasten the compressable to the body, while tapping into the cultural and fashion association of these materials.
- **Sewing** The seams of the compressables can be used for non-structural sewing techniques. A saddlestitch can be used to hand sew bladders onto fabrics, leathers, and other substrates. We use this technique to sew a delicate lace onto the edges of a bladder on a thigh to evoke the visual language of a garter. This is also a viable method for affixing beads, sewable electronics, or for integrating bladders onto 3D substrates.
- **Sowing** Sowing refers to our technique for implanting solid elements, or tacks, onto the surface of a bladder using an uncured layer of silicone. The tacks must fulfill the requirement of having a wide brim — this is to allow silicone to encapsulate a large surface area of the tack; otherwise the tack can be easily dislodged. We use this technique with conical tacks (4 mm ⌀ x 4 mm H). When coupled with an inflating bladder, these tacks can be made to "dig into" the skin, creating a blunt clawing sensation. More subtle haptic sensations are possible, especially since the haptic profile of bladders is constrained to the hardness of the material. Embedding tacks diversifies silicone from simply being a soft material, with opportunities to create more metamaterials with a wider range of haptic expressions.
- **Texturing** Many of these techniques utilize silicone's property of fusing with itself. Similarly, a texture can be added to a bladder by placing the bladder over a layer of uncured silicone in a texture mold. Texture molds are 3D printed molds containing tactile geometries. We include a set of texture molds in our toolkit for adding stripe, dot-grid, and wave-like textures; tactile directionality can also be controlled by reorienting the bladder within these molds. These textures pull the skin when bladders are inflating, creating subtle but noticeable dragging sensation.

Figures 5, 7, and 9 show examples of these fixturing methods in fully formed compressables.

5.2 Haptic Interaction Design Tool

Once a bladder has been fabricated and integrated with a wearable form factor, the compressable is connected to a pneumatic controller with an air tube with barbed and quick-connect fittings. CPT provides an interaction design tool that allows rapid, opportunistic and open-ended haptic interaction design for the compressables. The tool allows a user to quickly and wirelessly explore different haptic behaviors of the compressable in real time. The full system is depicted in Figure 3A. The utility of the design tool is based on a simple IoT communication infrastructure that allows seamless wireless communication between a *pneumatics controller*, a *gesture recognizer*, and one or many phones that run a *haptic designer* standalone web app that can allow a user to draw and send haptic behaviors to the compressables, trigger pneumatic actions, or bind gesture events to actions.

5.2.1 Sketching Interactions. The haptic designer tool exposes sketch-based interaction for sending commands to the haptic controller (Figure 3B). In **instantaneous mode**, the designer instantly changes the pump and vacuum power through a drag-and-release gesture to help a user achieve a comfortable **steady state** for a given compressable. In **temporal mode**, the designer offers a **gesture canvas** that allows a user to sketch haptic behaviours and trigger pneumatic commands to achieve the behaviors. This canvas abstracts individual valve and motor control to a single waveform gesture – points above the midline trigger the blow configuration and control the pump's power; conversely, points below the midline trigger the

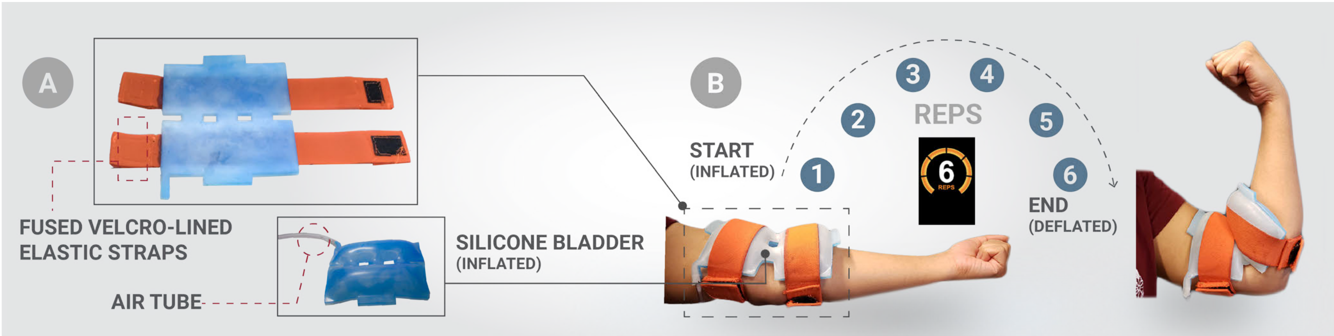


Figure 7: Elbow brace. A: An air bladder is fused with velcro-lined elastic straps and worn on the inside of the elbow joint; B: The inflated bladder tracks bicep curls and deflates upon completion of a set.

vacuum configuration. Haptic behaviors are **stored** as sketches and can be retrieved at any time from a storage toolbar. The tool allows the stored haptic behaviors to be bound to gesture events using an if-this-then-that (IFTTT) interaction pattern in a Collaboratory Notebook. The interface also allows a user to switch between right- and left-handed mode to facilitate single-handed operation. Lastly, for safety as well as comfort, the interface allows the user to set upper and lower **power limits** to prevent the compressable from over-inflating or to limit haptic compression.

5.2.2 Squeeze Gesture Recognition. User input on a compressable can be recognized using a pressure sensor. Our squeeze gesture recognition process follows traditional activity recognition workflows: (1) pressure sensor readings are collected into windows (8kHz sampling rate, 500 ms window size), (2) the window is processed and cleaned (low pass filter), and (3) the resulting window is classified based on the features of the gesture to determine its state (passed through a Sobel kernel ($[-2, 0, 2]$ and compared to a local running average). Inspired by Buxton's three-state model [1] (`DOWN-HOVER-UP`), the recognition routine identifies four possible states of a compressable (Figure 8): (1) `STASIS`, or when the bladder's air pressure is stable, (2) `SQUEEZE_HOLD`, or when the bladder is under a load, and (3/4)`SQUEEZE_START` and `SQUEEZE_END`, marking a change between exiting and entering stasis.

Implementation Details A cloud-based **websocket server** (Ruby EventMachine) is used to coordinate messages between a set of client devices. The communication protocol is straightforward: the server only accepts messages formatted as a JavaScript Object Notation (JSON) string and will broadcast this message to all clients connected to the server except the original sender. The **web application** was built as a standalone web app using Ruby on Rails and paperscript, while the squeeze gesture recognizer was implemented in Python. We used an off-the-shelf and open-source **pneumatic controller** (Programmable Air[4]). This controller consists of an air pump, a vacuum, three pneumatic valves for air flow control, and a pressure sensor - together, this device allows for the pneumatic control of one bladder. Like most pneumatics controllers, it requires significant power to drive its motors and solenoids (24W), tethering it to a non-wearable power supply. The Programmable Air is retrofitted with a WiFi-enabled microcontroller (Adafruit Feather MO ATWINC1500) using the Air's serial interface. The WiFI microcontroller is programmed to act as a Websocket client, connect to the websocket server, and expose Programmable Air API points. This allows us to bypass traditional upload-compile hardware prototyping routines and instead program these devices on-the-fly.

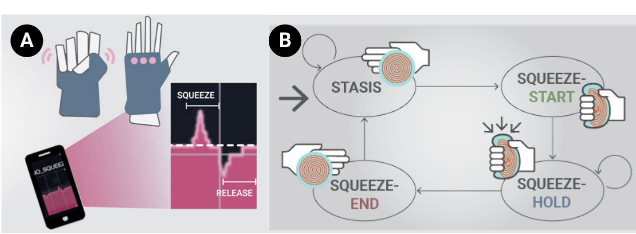


Figure 8: Compressables State Machine for Squeeze Gesture.

6 EVALUATION BY DEMONSTRATION

Evaluation by demonstration has been used to provide an indication of a toolkit's feasibility, extensibility, and expressiveness [14], especially as a way of annotating emerging design spaces. The goal of this demonstration is to operationalize how the different components of the toolkit can be used together to engender compression-based haptic input and feedback and to demonstrate the *paths of least resistance* enabled by the toolkit. We construct three exemplar compressables that sample across different size, placement and forces, and privacy in order to describe the bounds of what the toolkit can support. We additionally annotate each exemplar with their respective programmatic costs of integrating these compressables into more complex interactive systems. The resulting exemplars are used to facilitate a discussion with participants in a formal user study.

6.1 Stress Glove

In our walkthrough interaction (Section 4), we described the development of a stress-ball glove interaction (Figure 5) where a four-chamber bladder was fused to a fingerless glove above the distal palmar region of the hand. When worn, the bladder inflates

[4]https://www.programmableair.com/

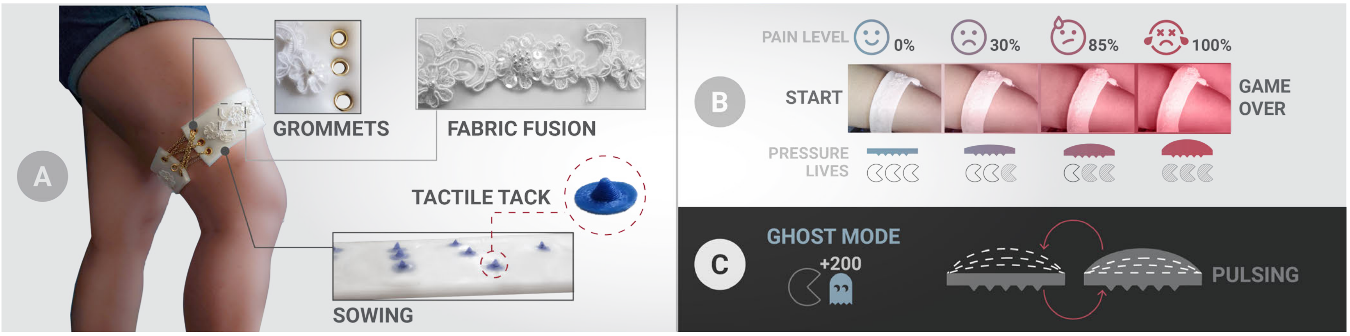
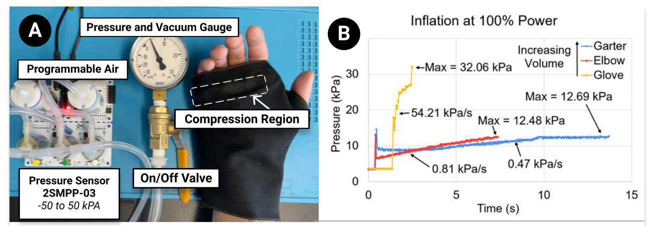


Figure 9: Garter. A: An air bladder sowed with tactile tacks is held around the thigh using a gold chain; B: The bladder inflates on loss of life in a Pacman game and deflates on game over; C: The bladder pulses in ghost mode.

to provide the wearer with a dynamic stress ball. In contrast to common sites for haptic interactions like the wrist or fingers, we found that the distal palmar region is well suited for compression-based haptics, causing a curious and unique haptic sensation caused by the bladder non-uniformly pulling this non-planar skin region. The toolkit supported this discovery by allowing us to quickly test pneumatic behaviors on different parts of the body. The fabric fusion method enabled the user to wear the compression mechanism like a regular clothing article while maintaining privacy, highlighting the wearability of the toolkit. The interaction was live programmed and uses a SQUEEZE_START event to trigger the bladder to inflate to a higher pressure; the inflated bladder is dismissed with a subsequent SQUEEZE_START event (change to base program: 5 lines of code).

6.2 Elbow Brace

While compressables are often used as feedback mechanisms, we explore how a compressable can be a more active force on the body. We found that a compressable that sits on a joint can be used to immobilize the joint or provide resistance. The *elbow brace compressable* is inspired from joint braces used to treat or prevent repetitive stress injuries and explore how disabling movement can aid actions such as exercise or physical therapy (Figure 7). The bladder is composed of two large chambers that fold along the common edge. It sits across the upper arm and lower arm with its midsection sitting directly on top of the elbow joint. We use the fabric fusion method to attach velcro-lined elastic straps to the compressable. When a wearer curls their bicep, the pressure in the bladder reliably mirrors a regular squeeze interaction. We leverage this property to sense curling actions in an exercise tracking interaction: we emit a REP event for each time a SQUEEZE_START event is logged; we keep a count of the number of reps and emit a SET event (change to base program: 6 lines of code). A meter view on the user's phone updates on each REP event, tracking the wearer's progress in the exercise routine; however, a short pulse haptic behavior marks the end of a set reducing the need to lend visual attention to screens. The CPT toolkit allowed us to visualize how bladders respond to different action through the live sensor feed and develop an activity tracker. While designed for the elbow, this compressable sits well on knee joints to track squats and lunges and with a slight modification can also operate on shoulder joints.



	Area (cm²)	∂P/∂t (kPa/s)	Inflation (s)	Deflation (s)
Glove	11.6	54.2	2.5	2.6
Elbow Brace	165.3	0.8	7.1	7.4
Garter	171.2	0.5	13.7	33.3

Figure 10: Compressables Pressure Characterization. A: Characterization Setup; B: Inflation Times at 100% pressure; C: Bladder Properties and Pneumatic Characteristics.

6.3 Garter

We explore the use of complementing compressive forces with stronger haptic sensations. By sowing rigid tacks on a compressable, we were able to generate a blunt clawing sensation. When placed along the thigh, this garter was used to create an immersive gaming experience (Figure 9). The clawing can be used to highlight the loss of a life or a limb in a game and the thigh provides a large, unexplored, muscular surface area where the sensation feels prominent without being overwhelming. The *garter* is affixed around the thigh using grommets and a gold chain, and lace is fused on the outside trim. We sowed 21 tacks (4 mm ⌀ x 4 mm H) in diagonal columns (10 mm row pitch, 30 mm column pitch) onto the surface in contact with the skin. Using the haptic design tool, we explored different haptic sensations that could be used to enhance gameplay. We modified an open-source implementation of the popular arcade game Pac-Man[5] by emitting websocket messages in select areas of the game, such as when a player DIEs, EATs tokens, or WINs (diff: 10 lines of code + 1.5kb uncompressed library). Our interaction logic a) binds an INFLATE action to a DIE event – when a player loses a life in the game, the garter inflates intensifying the clawing sensation;

[5]https://github.com/luciopanepinto/pacman

b) when lives counter reaches zero, the garter deflates completely and the clawing sensation abates; c) during GHOST_MODE, a special mode where the player avatar is granted a time-constrained ability (e.g., enemy-eating capabilities), we bind to a PULSE interaction, intensifying the excitement and risk of gameplay.

6.4 Technical Characterization

Due to the difference in the size, placement, and compression mechanism of each compressable, we conducted a systematic experiment to characterize their respective pneumatic characteristics. We first calibrated the Programmable Air 2SMPP-03 pressure sensor against a standard pressure and vacuum gauge (Figure 10A). We then logged sensor readings, sampled at 8Hz, and used non-destructive testing to determine the maximum pressure, inflation, and deflation times of all three exemplars. When determining the maximum pressure a bladder could withstand, the bladders were filled at the highest possible rate (100% Power), and the maximum pressure was recorded at the visual bursting point. The reported deflation times correspond to the time for a bladder to return from this fully inflated state with no active vacuum.

Figure 10B demonstrates the variance in inflation behaviors - when inflated at 100% pump power, each exemplar compressable exhibits a range of inflation rates. The sharp peaks in the graph correspond to opening and closing the valve, showing the redistribution of air across the pipes. The garter was succeptible to curling, making it difficult to deflate afterwards. Large volume compressables inflated more consistently, whereas much faster compression could be achieved with low volume bladders(Figure 10C).

7 USER STUDY EVALUATION

Due to the limited vocabulary around haptic design [31], we conducted a formal user study with novice interaction designers to assess the Compressables Haptic Toolkit's ability to support creative ideation and exploration of compression-based haptic behaviors. The study also provides user descriptions of the range of haptic sensations experienced by users when wearing our exemplars.

7.1 Recruitment and Participant Selection

We submitted messages through local listservs within the Art, Design, and Engineering departments at our local university. Due to COVID-19 pandemic precautions, only participants 18-65 years old were eligible for study. Participants were selected from a prescreening survey consisting of 5-point Likert statements assessing familiarity with wearables and interaction design. Only participants with self-reported ratings below 3 were asked to participate. Our final study group consisted of six participants (3 female, 3 male) who all reported exposure to wearables, largely from activity trackers.

7.2 Study Design

For each session, participants were asked to individually meet with us in our design studio. Participants were paid $10 USD for a one-hour session consisting of a fabrication walkthrough, a haptic behavior design task, and a compressables brainstorming session. Participants were asked to engage in a think aloud throughout the study, specifically describing their design intentions, haptic perceptions, and any reactions to the usability of the toolkit.

Fabrication Walkthrough. Due to the limited study duration, we were not able conduct a workshop for fabricating a compressable; we did conduct a fabrication walkthrough to demystify the process. Using the stress glove as an example, we showed design and model files and a video of the 3D printing and lost-PVA casting process. We then mimed the procedure in our silicone workstation, the pattern fabrication and sewing, and lastly the fixturing process. We then asked participants to describe processes or techniques that remained blackboxed.

Arcade Game Haptic Design. Participants were introduced to our haptic designer and briefly walked through the different input modes, fail-safe switches, and behavior saving functionality. We then tasked participants to design haptic interactions for the Pac-Man arcade game for 10 minutes (Figure 11). Participants could elect to use a textured or tacked 50 mm spherical compressable attached with velcro to their non-dominant hand. A Google Collaboratory notebook allowed the participant to specify which behaviors from their exploration (A-D) would be triggered when the game entered GHOST_MODE, or when a DEATH event occured (conditioned on remaining lives). Participants could play the game at any point during the design session. We administered the creativity support index (CSI), a psychometric survey grounded in creativity support tools literature which measures how well a tool "assists a user engaged in creative work" [3].

Brainstorming Activity. Participants were asked to wear and explore different haptic expressions using our haptic designer. We then conducted a brainstorming session with the participant for compressables interaction ideas. Participants were presented with a series of cards depicting 20 different regions of the body. We asked a series of semantically-anchored 5-point Likert statements relating to design potential of compressables and asked the participant to cluster the cards according to their rating. Participants created Wizard-of-Oz interactions with our example compressables

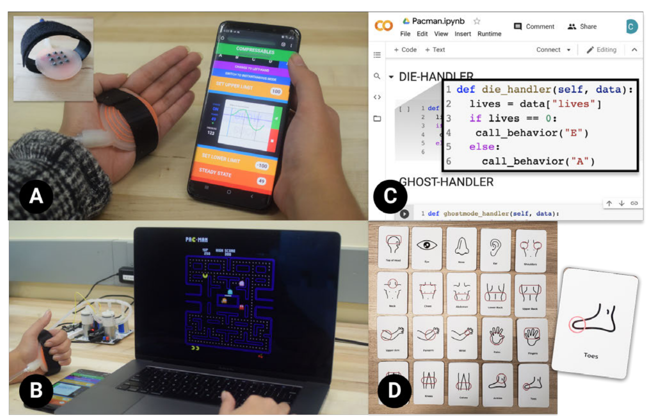


Figure 11: User Study Setup. A: Users tested behaviors using the designer app and a tacked velcro-bound spherical compressable; B: Users integrated their behaviors to our API using Google Collaboratory; C: Users played Pacman to test their behaviors; D: Users brainstormed design potential and interaction ideas for different body parts

to assess the feasibility of their ideas. The cards were also used to probe reflections of the overall design process.

7.3 Results

7.3.1 Fabrication and design perceptions. While some users expressed familiarity with 3D printing and textile form-giving, all users unanimously reported no experience with silicone-based fabrication. We were encouraged to find that despite the novelty, users found comfort and direction in our step-by-step video tutorial. Five out of six users perceived the fabrication as easy to replicate using our tutorial, while one user anticipated requiring outside help.

> **C36** I think the fabrication step is simple, there are not many steps so I can do it if I see the tutorial.

Some users expressed hesitancy about operating a vacuum chamber. They were more confident once we demonstrated the workflow of using the chamber and reiterated that the step is optional and does not drastically affect the structural integrity of the compressable. Users were wary about the lack of flexibility in remodeling a fully fabricated compressable.

> **C48** What if I make a compressable but it doesn't turn out to be what I want, it seems that it increases fabrication cost by a lot.

They were, however, excited to see the variety in our set of pre-fabricated molds. We were encouraged to see that some users started to visualize mold designs for locations outside of our chosen set such as for the neck and shoulders during the walkthrough.

7.3.2 Haptic behavior design and the experience. Users quickly grasped the functionalities of the designer tool and felt agency towards translating their design intentions onto the gesture canvas. After tentative experimenting with "safer" (simple sine wave patterns) behaviors to test the limits of the compressables, users became bolder with their patterns, trying to emulate physical phenomenon such as a heartbeat or to convey an emotion such as chaos. The high enjoyment ratings (8.1/10) and expressiveness score (7.5/10) in the CSI survey reflected user's ability to find creative variation in a simple sketch gesture:

> **C72** I think the app is very user-friendly, I learned how to use it in a minute or so and can make the compressable exhibit all these different behaviors, and I've never worked with a system like this before.

> **C96** I'm really glad you took into consideration whether a user is right-handed or left-handed. It makes a big difference for me when I'm drawing the behaviors.

Users were excited about the collaboration potential of the designer app, with their intentions ranging from assistive to playful.

> **C72** I can see myself using this option to remotely send alerts to someone wearing a compressable, for example to remind them to take their medication.

> **C96** It would be so fun to use this to send a friend a random pulse when they are least expecting it and watch them freak out.

Users were pleased by the ease with which they could integrate haptic behaviors into the Pac-Man game, as reflect in the CSI results worth effort score (8.3/10). The experience demonstrated the design potential of the toolkit and inspired users to think outside the box.

> **C36** I was thinking the only type of interaction you would be able to have with the compressables are like notifications, but now I see that you could do so much more and so easily and it makes me think of all the possibilities.

Multiple users expressed interest in making the gestures time-sensitive through the app. Although achievable programmatically, users felt limited in their behavior design by not being able to control the duration of the gestures.

7.3.3 Assessing the repertoire of haptic expressions in exemplar compressables. Users varied in their depictions of the haptic sensations provided by the exemplar compressables. Users appreciated the discrete nature of the stress glove, citing the inconspicuousness of the therapeutic interaction. Users reported sensations in the range of barely feeling any compression to feeling a strong compressive force when the bladder is inflated based on the fit of glove.

> **C36** The glove is kind of loose, so I only feel a pressure when you inflate the bladder all the way up. It's more apparent when I close my fingers over it or when you slowly release the air.

> **C72** The glove fits like one I regularly wear. When you inflate the bladder, it feels like someone is gripping that area. I can also differentiate between the circular air chambers which is pretty cool.

Users agreed that the elbow brace provided similar sensations to a blood pressure cuff, with the sensation becoming more prominent upon curling the arm. Users found comfort in the compressables lightness (weight) and were motivated to wear it due to its aesthetic qualities.

> **C72** I love how light it is and how nice it looks! When I think of wearable technology, I always imagine it to consist of lots of circuitry and I don't really want to wear motors and wires, but this I would wear happily.

We simulated the garter sensation using a tacked circular compressable affixed against the palm with a velcro strap (Figure 11). We still showed the garter to gauge user's opinions of the wearability of the artifact. Some users were reluctant to wear the garter, citing discomfort in having to wear it under clothing that covers the thighs such as jeans or leggings, but were open to situations where the garter was not restricted.

The tactile tacks sowed to the circular compressable were well-received. Rather than being intimidated by the possibility of pain, users were inspired to find new ways to incorporate the structures to their own design. Users reported the clawing sensation to be prominent and attention-grabbing but not discomforting.

> **C72** They remind me of the tips of a back-scratcher. The pain level increases when I inflate the bladder, but even when I inflate it all the way, it doesn't feel uncomfortable.

7.3.4 Locating compressables. Users found value in the body cards, citing that the visualization made them consider locations they would not typically think of. Although there was no consensus on a location for most or least design potential, multiple users found the shoulders to be a prime design location. Users envisioned a

Factor	Factor Count 15 pts total	Factor Score out of 20 pts	Weighted Score avg. count x score
Exploration	1.33 (0.80)	17.50 (0.92)	24.50 (15.90)
Enjoyment	3.00 (0.73)	16.33 (1.33)	46.67 (10.65)
Results Worth Effort	1.67 (0.71)	16.67 (1.09)	29.33 (12.29)
Expressivity	2.83 (0.75)	15.17 (1.22)	47.17 (14.66)
Immersion	2.50 (0.62)	16.50 (0.56)	41.67 (10.20)
Collaboration	3.67 (0.21)	17.50 (0.76)	64.17 (4.68)
		CSI Score (out of 100)	84.50 (3.88)

Figure 12: Creativity Support Index rating averages and standard error. A factor count represents a user's preference for creativity support dimensions and is used to weigh a user's factor score for each dimension. Factor scores are composed of two 10-pt Likert scale statements for each factor. The final score should be read like a letter grade (A-F scale).

range of interactions for the shoulders, from time-sensitive posture correction to weight simulation in virtual reality.

We were encouraged to find a variety in the settings and tasks in which users considered the toolkit useful.

> **C36** I work at a glass blowing studio, and there are a lot of time-sensitive tasks. I was thinking of making the compressable deflate with time to silently indicate how much time I have left before I have to attend to a task.

> **C48** I can see myself wearing a tacked compressable in the car, if I'm getting sleepy, it can inflate and the pain can wake me up.

The range in the user's responses for design potential explains the high exploration score on the CSI analysis (8.75/10) as the toolkit provided users with the opportunity to think through and test different haptic behaviors.

8 DISCUSSION

Due to pandemic precautions, user studies were limited to a one-hour socially distanced study session. While we designed ways of scaling a compressables design task to the constrained study period, we supplement the internal validity and extended use of the toolkit using UI system guidelines proposed by Olsen [20]. These heuristics have been used as toolkit-centric design guidelines to assess a toolkit's strengths, weaknesses, and potential [14]. We discuss the technical characterization, evaluation by demonstration and user study results juxtaposed against **Olsen's heuristics** (annotated in boldface) to provide a more complete picture of the opportunities and limitations of compression-based haptics.

8.1 Haptic sketching requires a focus on active perception

In the haptic design tool, we introduced a layer of abstraction around pneumatic controls by converting an expressive sketch gesture into specifications for two valve states and two motor powers over a function of time. These waveforms are common ways to encode high-level haptic behaviors found in popular vibrotactile controllers (DRV2605L) and other forms of actuation [11, 34]. Through pilot studies of the tool, we increasingly found that exploration of haptic sensations was limited by short-term haptic memory. We found that haptic design's **solution viscosity**, or the effort to iterate on design solutions, is dependent on the ability to fully attend to the perception of the stimulus and minimize the time and cognitive load between tests. By focusing our design on single-hand operation, it allowed users to dedicate a hand towards active perception. Furthermore, by converting power specification to an anchorless slider gesture, users were able to tune the base pressure of the compressables without looking at a screen. Lastly, storing and loading previous haptic gestures allowed users to quickly compare-and-contrast haptic behaviors.

8.2 IoT interactions invite new design participants

We used an Internet of Things communication architecture for our haptic design toolkit. This design choice provided significant **flexibility** over traditional wired and centralized architectures, as had been previously identified by the SoD-Toolkit [29] – the socket architecture supported low-friction integration, **simplifying interconnection** with Arduino, Jupyter and Google Collaboratory notebooks, and Javascript clients. This configuration also supported multiple users on multiple phones to open our web application and control the compressable artifact simultaneously to support collaborative haptic brainstorming. The **flexibility** of creating different compressable form factors also resulted in a diverse range of pneumatic characteristics, as evidenced by our technical characterization of the exemplar bladders. While many systems require systematic calibration [12], the live programming capability our architecture allowed users to move between different compressables and adjust parameters without needing to recompile or flash code to hardware components. Together, this distributed environment reduced the need to have expertise in a programming language or electronics, which lowers the barrier for the **new design participants** to be able to create haptic interactions. This architecture further enables integration with other external sensors. For example, CPT can be used to fabricate a pair of dynamic earplugs that activate from sound levels from a connected microphone. The stress glove can also bind to electrodermal activity, often used as an indicator of stress, to create more context-specific interactions.

8.3 Decoupling electronics improves wearability

Compression-based haptic wearables are often weighed down by bulky and cumbersome compression mechanisms [5, 12, 25]. Since pneumatic control is self-contained (not on the worn artifact), the toolkit supported exploratory plug-and-play behaviors, readily allowing us to swap control between different prototypes without needing to reconfigure electronics. Because the compressable mechanism is passive, it eliminates the need to reset or recharge the worn mechanisms and can continue to be used even when disconnected from the pneumatic controller as a wearable artifact or clothing article such as the glove. This also allows the compressables to be machine-washable, while maintaining flexibility, softness, and comfort without damaging electronics. Interfacing with fabrics also improved the aesthetic qualities of the compressable; non-flexible fabrics were used to constrain the bladder against the skin, augmenting the compressive sensation.

We created compressables for different regions of the body including the distal palmar region, elbow joint, and thigh, each form factor presenting a set of unique challenges. These regions differed in size, haptic sensitivity, aesthetic traditions, and social perceptions of privacy. The set of fixturing methods provided a means of **inductive combination**, or building more complex designs from primitive design choices. These fixturing methods allowed access to the larger traditions and material aesthetics of textiles, affixing bladders to different textile materials to provide additional structure (e.g., fusing velcro straps in the elbow brace), aesthetic (e.g., using a gold chain and grommets to evoke preciousness), or haptic (e.g., sowing tacks on an air bladder to provide a clawing sensation) functions. Multiple prototypes of each compressable were also supported by reusing molds. We see additional opportunities to borrow from textile formgiving practices to support adaptability of garments. The stress glove positioned a bladder on the palmar region, but this required additional calibration to rest in the right location for different hand sizes. Large bladders (e.g., a compressable back-brace) remain a fabrication challenge - while we leveraged laser-cut molds to support larger compressables, the PVA seperator still needs to be 3D printed. Multiple PVA separators can be water-welded, but this adds to fabrication errors. Laser cuttable PVA sheets can be one way to support larger bladders or using alternative water-dissovable materials (e.g., rice paper).

8.4 Limitations

One major design limitation of the toolkit is using a pneumatics controller that is tethered to a 24W power supply and echoes the challenges of other compression-based mechanisms such as shape-memory alloy [2, 8, 10, 30]. While researchers have explored backpack strategies, power still remains an issue for mobile use. Compared to other compression-based haptic wearables with bulky and cumbersome compression mechanisms [5, 12, 25], our decoupled design supports better wearability (soft, lightweight, standalone, and comfortable to wear). By decoupling the controller from the worn artifact, the tether on the user is not a electrical cord, but instead an air tube which affords a safer, cheaper, and more easily configurable connection.

We view the space of compressables as viable in situations and environments where constrained mobility is acceptable such as workstations like a desk or workbench, or in physical therapy and medical settings where professionals work in sedentary positions. Alternatively, many workshop environments have a pressurized air infrastructure that can be used to support compression-based haptics. CPT decouples active and passive mechanisms in a compressable allowing interactions where a user walks up and quick-connects to a pneumatic-controllable airtube. While our off-the-shelf controller is limited to a single air outlet, our IoT approach supports **the ease to combine** multiple haptic controllers distributed across a space. However, as is common with pneumatic controllers [41], the pump and vacuum motors generate a continuous droning sound and a clicking sound is associated with the opening and closing of the solenoid valves. Such noise may be expected and even appreciated in creative workshop settings where the droning of the motors acts almost like white noise in constant pressure interactions. However, the continuous clicking of the solenoid valves in interactions such as pulsing can be distracting in scenarios where silence is important. We see opportunities in using 2-way or 3-way solenoid valves for their quiet no-click operations for the controller in the future. Lower-power and wearable valves will further allow **scaling** the control more than one compressable on the body and remove the need to fabricate large and expensive molds for large compressables. There also remain challenges in scaling the number of devices on the network, especially since sensor streaming can throttle system bandwidth. In the future, we see opportunities for compressables to be filled with vinegar, baking soda, water, yeast, and sugar to create a single-use inflation mechanism; similarly, we see opportunities in developing a hydraulic-based system that could enhance haptic sensations through water flow and temperature change.

Technical Limitations In order to satisfy **inductive combination**, a toolkit needs to be able to build complex designs by combining a limited set of primitive design choices. Our haptic designer combines pump and motor control as a single sketch-based gesture that enables a wide expression of temporal haptic behaviors. However, there was a disconnect between the interpretation of the sketch and the response of the system, largely due to the large hysteresis and non-linear behaviors, or more concretely, (1) when a large bladder is inflated, an increase in pump power will produce a less pronounced effect than on a small bladder, and (2) the more a bladder is inflated (increasing pressure), the quicker it will deflate. The shared visual languages of haptic sketches served well as a form of documentation and communication as users built their respective mental models and refined their understanding of the pneumatic system's limitations. We view this as a design direction closely aligned with the concept of material encounters [19] that allow users to develop craft-based knowledge. There remain opportunities to adjust user-drawn sketch instructions to emulate the system's response. These could be synthesized into drawing rules — for example, accounting for hysteresis would involve limiting the slope the of the line being drawn; to adjust for non-linear deflation responses, lines drawn under the current state of the system could be plotted on an exponential scale.

9 CONCLUSION

In this work, we present the Compressables Prototyping Toolkit to support the rapid prototyping of compression-based haptic feedback. Through a set of fixturing methods, we unified the available set of techniques for configuring inflatable silicone bladders to wearable form factors. We demonstrated the utility of these fixturing methods through exemplar artifacts that showcase the contextually-rich and underexplored regions of the body including the palm, elbow joint, and thigh. We expanded compression-based haptic design capabilities through a haptic designer app that allows experiential testing of haptic behaviours through sketching. By retrofitting an off-the-shelf pneumatic controller with wireless capabilities, we removed tedious upload-compile physical computing workflows to instead support on-the-fly and distributed programming interactions using classic event handler and listener architecture. We validated the effectiveness and open-endedness of our toolkit through a user study and heuristic evaluation. We also designed exemplar compressables to annotate the design space of compressables and diversify the range of haptic forms and expressions on the body.

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REFERENCES

[1] William Buxton. 1990. A three-state model of graphical input. In *Human-computer interaction-INTERACT*, Vol. 90. Citeseer, 449–456.

[2] George Chernyshov, Benjamin Tag, Cedric Caremel, Feier Cao, Gemma Liu, and Kai Kunze. 2018. Shape memory alloy wire actuators for soft, wearable haptic devices. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. 112–119.

[3] Erin Cherry and Celine Latulipe. 2014. Quantifying the creativity support of digital tools through the creativity support index. *ACM Transactions on Computer-Human Interaction (TOCHI)* 21, 4 (2014), 1–25.

[4] Richard Lee Davis, Melisa Orta Martinez, Oliver Schneider, Karon E MacLean, Allison M Okamura, and Paulo Blikstein. 2017. The haptic bridge: towards a theory for haptic-supported learning. In *Proceedings of the 2017 Conference on Interaction Design and Children*. 51–60.

[5] Alexandra Delazio, Ken Nakagaki, Roberta L. Klatzky, Scott E. Hudson, Jill Fain Lehman, and Alanson P. Sample. 2018. Force Jacket: Pneumatically-Actuated Jacket for Embodied Haptic Experiences. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, Montreal QC, Canada, 1–12. https://doi.org/10.1145/3173574.3173894

[6] Jonas Forsslund, Michael Yip, and Eva-Lotta Sallnäs. 2015. Woodenhaptics: A starting kit for crafting force-reflecting spatial haptic devices. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. 133–140.

[7] Radhika Ghosal, Bhavika Rana, Ishan Kapur, and Aman Parnami. 2019. Rapid Prototyping of Pneumatically Actuated Inflatable Structures. In *The Adjunct Publication of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 78–80.

[8] Aakar Gupta, Antony Albert Raj Irudayaraj, and Ravin Balakrishnan. 2017. HapticClench: Investigating squeeze sensations using memory alloys. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. 109–117.

[9] Sebastian Günther, Dominik Schön, Florian Müller, Max Mühlhäuser, and Martin Schmitz. 2020. PneumoVolley: Pressure-based Haptic Feedback on the Head through Pneumatic Actuation. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery, Honolulu, HI, USA, 1–10. https://doi.org/10.1145/3334480.3382916

[10] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jürgen Steimle, and Jan Borchers. 2019. Springlets: Expressive, flexible and silent on-skin tactile interfaces. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–14.

[11] Chris Harrison, John Horstman, Gary Hsieh, and Scott Hudson. 2012. Unlocking the Expressivity of Point Lights. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 1683–1692. https://doi.org/10.1145/2207676.2208296

[12] Liang He, Cheng Xu, Ding Xu, and Ryan Brill. 2015. PneuHaptic: delivering haptic cues with a pneumatic armband. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers*. 47–48.

[13] Jonggi Hong, Alisha Pradhan, Jon E Froehlich, and Leah Findlater. 2017. Evaluating wrist-based haptic feedback for non-visual target finding and path tracing on a 2d surface. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility*. 210–219.

[14] David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. 2018. Evaluation strategies for HCI toolkit research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–17.

[15] David Ledo, Miguel A Nacenta, Nicolai Marquardt, Sebastian Boring, and Saul Greenberg. 2012. The HapticTouch toolkit: enabling exploration of haptic interactions. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*. 115–122.

[16] Qiuyu Lu, Jifei Ou, João Wilbert, André Haben, Haipeng Mi, and Hiroshi Ishii. 2019. milliMorph–Fluid-Driven Thin Film Shape-Change Materials for Interaction Design. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 663–672.

[17] Tomosuke Maeda and Tetsuo Kurahashi. 2019. Haptiple: A Wearable, Modular and Multiple Haptic Feedback System for Embodied Interaction. In *SIGGRAPH Asia 2019 Emerging Technologies*. 19–20.

[18] Hedieh Moradi and César Torres. 2020. Siloseam: A Morphogenetic Workflow for the Design and Fabrication of Inflatable Silicone Bladders. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1995–2006. https://doi.org/10.1145/3357236.3395473

[19] Michael Nitsche and Anna Weisling. 2019. When is It Not Craft? Materiality and Mediation When Craft and Computing Meet. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 683–689. https://doi.org/10.1145/3294109.3295651

[20] Dan R Olsen Jr. 2007. Evaluating user interface systems research. In *Proceedings of the 20th annual ACM symposium on User interface software and technology*. 251–258.

[21] Jifei Ou, Felix Heibeck, and Hiroshi Ishii. 2016. TEI 2016 Studio: Inflated Curiosity. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. 766–769.

[22] Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. 2016. aeroMorph-heat-sealing inflatable shape-change materials for interaction design. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 121–132.

[23] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo. 2017. Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives. *IEEE Transactions on Haptics* 10, 4 (2017), 580–600.

[24] Max Pfeiffer, Tim Duente, and Michael Rohs. 2016. Let your body move: a prototyping toolkit for wearable force feedback with electrical muscle stimulation. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 418–427.

[25] Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. 2017. Squeezeback: Pneumatic Compression for Notifications. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Denver Colorado USA, 5318–5330. https://doi.org/10.1145/3025453.3025526

[26] Ingrid Maria Pohl and Lian Loke. 2014. Touch toolkit: a method to convey touch-based design knowledge and skills. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. 251–258.

[27] Cristina Ramírez-Fernández, Alberto L Morán, and Eloísa García-Canseco. 2015. Haptic feedback in motor hand virtual therapy increases precision and generates less mental workload. In *2015 9th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth)*. IEEE, 280–286.

[28] Stefanie Schaack, George Chernyshov, Kirill Ragozin, Benjamin Tag, Roshan Peiris, and Kai Kunze. 2019. Haptic Collar: Vibrotactile Feedback around the Neck for Guidance Applications. In *Proceedings of the 10th Augmented Human International Conference 2019*. 1–4.

[29] Teddy Seyed, Alaa Azazi, Edwin Chan, Yuxi Wang, and Frank Maurer. 2015. Sod-toolkit: A toolkit for interactively prototyping and developing multi-sensor, multi-device environments. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces*. 171–180.

[30] Melanie F Simons, Alice C Haynes, Yan Gao, Yihua Zhu, and Jonathan Rossiter. 2020. In Contact: Pinching, Squeezing and Twisting for Mediated Social Touch. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–9.

[31] Vicky Teinaki, Bruce Montgomery, Nick Spencer, and Gilbert Cockton. 2012. An aesthetics of touch: Investigating the language of design relating to form. (2012).

[32] Carlos E Tejada, Raf Ramakers, Sebastian Boring, and Daniel Ashbrook. 2020. AirTouch: 3D-printed Touch-Sensitive Objects Using Pneumatic Sensing. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–10.

[33] Rundong Tian, Vedant Saran, Mareike Kritzler, Florian Michahelles, and Eric Paulos. 2019. Turn-by-wire: Computationally mediated physical fabrication. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 713–725.

[34] Cesar Torres, Molly Jane Nicholas, Sangyeon Lee, and Eric Paulos. 2019. A Conversation with Actuators: An Exploratory Design Environment for Hybrid Materials. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 657–667. https://doi.org/10.1145/3294109.3295643

[35] Cati Vaucelle, Leonardo Bonanni, and Hiroshi Ishii. 2009. Design of haptic interfaces for therapy. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. Association for Computing Machinery, Boston, MA, USA, 467–470. https://doi.org/10.1145/1518701.1518776

[36] Marynel Vázquez, Eric Brockmeyer, Ruta Desai, Chris Harrison, and Scott E Hudson. 2015. 3d printing pneumatic device controls with variable activation force capabilities. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 1295–1304.

[37] Rongrong Wang, Francis Quek, Deborah Tatar, Keng Soon Teh, and Adrian Cheok. 2012. Keep in touch: channel, expectation and experience. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 139–148.

[38] Gili Weinberg, Maggie Orth, and Peter Russo. 2000. The embroidered musical ball: a squeezable instrument for expressive performance. In *CHI'00 extended abstracts on Human factors in computing systems*. 283–284.

[39] Xuefei Yang and Stefania Druga. 2019. Legoons: Inflatable Construction Kit for Children. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*. 139–146.

[40] Nesra Yannier, Ali Israr, Jill Fain Lehman, and Roberta L Klatzky. 2015. FeelSleeve: Haptic feedback to enhance early reading. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 1015–1024.

[41] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and Technology*. 13–22.