SleeveIO: Modular and Reconfigurable Platform for Multimodal Wearable Haptic Feedback Interactions

Ali Shtarbanov
MIT Media Lab & Meta Reality Labs, Cambridge, Massachusetts, USA
alims@media.mit.edu

Mengjia Zhu
Meta Reality Labs Research, Remond, Washington, USA
mengjiazhu@meta.com

Nicholas Colonnese
Meta Reality Labs Research, Remond, Washington, USA
ncolonnese@meta.com

Amirhossein H. Memar
Meta Reality Labs Research, Remond, Washington, USA
amirmemar@meta.com

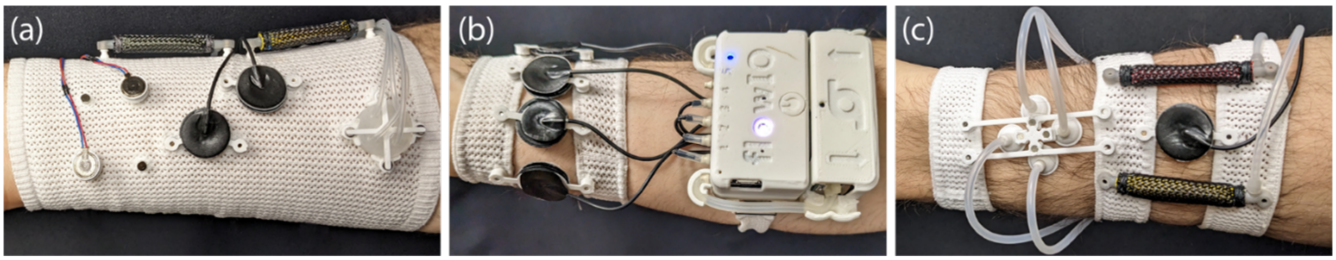

Figure 1: Example multimodal haptic feedback interactions enabled by SleeveIO: (a) Two vibrotactors, two bellows, two muscles, and a quad-chamber module on a knitted sleeve substrate; (b) Bellow modules on two knitted-band substrates with a wearable pneumatic control system; c) Suction cups, muscles, and bellow modules connected to three knitted-band substrates.

ABSTRACT

SleeveIO is a modular and reconfigurable hardware platform for rapid prototyping of multimodal wearable haptic feedback interactions. SleeveIO features engineered machine-knitted sleeve and band substrates, and five categories of haptic feedback actuator modules including vibrotactors, bellows, muscles, suction/puffing cups, and quad-chamber actuators. A universal magnetic attachment mechanism unifies the different types of actuators, enabling countless multimodal haptic experiences involving combinations of different actuator types in different configurations. SleeveIO is compatible with a variety of hardware/software control platforms, such as *FlowIO* [42], which enables individual control of each haptic actuator and makes the system battery-powered and untethered. This paper presents the SleeveIO platform in detail along with replication resources, a novel generalized approach to making different types of haptic actuators modular and interoperable, new application possibilities enabled by SleeveIO, and a pilot assessment of the viability of the platform as a whole and each module individually.

CCS CONCEPTS

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

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Haptics, Platform, Toolkit, Modular, Reconfigurable, Soft Actuator, Soft Robotics, Pneumatic, Prototyping, Knitting

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1 INTRODUCTION

Modern audio/visual interfaces and electronics development platforms feature impressive characteristics of modularity, interoperability, ease of use, and plug-and-play capabilities. These affordances and capabilities enable interaction designers, application researchers, and prototypers working with those technologies to seamlessly combine different hardware and software, electronics, and devices to rapidly test application ideas and to unlock new interaction possibilities. For instance, VR headsets, hand trackers, motion sensors, hardware development platforms, and various software frameworks - can rapidly be integrated with one another, allowing designers and researchers to then focus most of their effort on building new applications, without spending much time on the integration aspect of those technologies.

However, those high-level interoperability and plug-and-play characteristics that are common in the audio/visual and electronics domains are hard to find in the haptics domain currently. As a result, haptics researchers and haptics interaction designers often face far greater challenges when trying to combine different haptic technologies in order to create a new application. They often have to spend the majority of their time just on the integration aspect of the technologies they wish to combine, before being able to start developing the applications. They may have to find custom connectors, create new coupling mechanisms, develop new communication protocols, or may even have to modify from the ground up the technologies they wish to combine, just to make them interoperable and compatible with one another.

Conducting haptics research often requires creating "full stack" systems composed of custom-made components which are oftentimes incompatible with other projects. For instance, from 2017 to 2020 several haptic sleeve or wristband projects were published rendering similar haptic stimuli [10, 25, 33, 36, 38, 44, 45, 51]. However, despite their similarities, all of these research projects were constructed, implemented, and controlled in different ways – representing a substantial duplication of effort and making collaboration between different research teams difficult.

Inspired by the interoperability, modularity, and plug-and-play capabilities of consumer electronics and hardware development platforms, and by witnessing and experiencing the hardware-integration struggles faced by haptics researchers and designers, we began exploring the possibility of creating a standardized modular approach to wearable haptics that enables the seamless combination, reconfiguration, and adaptation of many different kinds of haptic actuators and actuation approaches. We wanted to provide an approach or a standard to wearable haptics so that haptics researchers have a way of adapting various past, present, and even future kinds of haptics actuators to be compatible with one another. And we also wanted to enable haptics interaction designers to be able to seamlessly create multimodal haptic user experiences with many different kinds of actuators without having to dedicate much effort on the integration aspect of the hardware and software and be able to focus on the applications instead. Thus, in this paper we present a new standardized approach to wearable haptics that achieves those goals. We also created a new haptics development platform called SleeveIO built in accordance with these objectives, while being untethered, modular, reconfigurable, and supporting combinations of many different types of haptic actuators. SleeveIO serves as both a demonstration of our proposed approach to interoperability that can be adapted by other researchers, and also as a design canvas that can be used by interaction design researchers to rapidly prototype novel user experiences or to test new combinations of actuators and placements of those actuators.

The key contributions of this paper are as follows:

- A novel modular and reconfigurable approach to wearable haptics, that enables the plug-and-play combination and reconfiguration of various novel and previously existing types of haptic actuators.
- A full-stack development platform and toolkit for wearable haptics that is modular, reconfigurable, conformable, and self-contained / untethered.
- An example set of five types of plug-and-play haptic feedback modules demonstrating how all of them have been adapted to use our unified magnetic interface.
- A repository of resources for replicating the SleeveIO system and each type of haptic module.
- Pilot assessment of the viability of SleeveIO and each type of module, and haptic experience comparison between modules.

2 OUR APPROACH

To address the problem of interoperability between different types of haptic actuators we identified four characteristics that had to be met: modularity, reconfigurability, support for many types of actuators, and support for multiple actuation approaches.

Modularity

Baldwin & Clark [3] define modularity as "Independence of structure and integration of function" – the structural units of a system are independent of one another but they work together. The ideal type of modularity is a full plug-and-play capability.

Reconfigurability

We define reconfigurability as the capability for repeated structural and functional transformations. The most relatable example of reconfigurability is a LEGO set. Reconfigurability is an essential feature for enabling arbitrary haptic user experiences.

Many Types of Actuators

To achieve general-purpose interoperability, our approach had to be suitable for not only one type of actuator with many variations, but also for many different types of actuators with multiple variations of each actuator. We needed to devise a common method for connection and coupling of distinct actuator types. It also had to allow actuators from prior works to also be easily adaptable to that common standard.

Multiple Methods of Actuation

We also have to account for the fact that wearable haptic devices can be actuated by many different technologies - including electromagnetic, pneumatic, biologic, thermal, and others. Thus, if we want to offer a designer the possibility to integrate a wide variety of haptic actuators, they need to have the freedom of using multiple methods of actuation.

Despite numerous advances in haptic platforms and haptic actuation, the prior works we found did not meet all four of our criteria above. Thus, we devised our own approach to satisfy these objectives. Inspired by educational pegboards into which pegs of different shapes and functions can be inserted anywhere on the 2D board to create art, we asked what if we make a 3D pegboard that is knitted, conformable, and wearable, and to which we can attach different kinds of haptic actuators to create diverse haptic user experiences.

Based on this approach, we built a development platform that is modular, reconfigurable, and supporting many different kinds of haptic actuators. It has a knitted substrate worn on the forearm to which various haptic actuator modules can be attached anywhere using magnetic cap-&-pole connectors. To provide multiple methods of actuation, we leverage the FlowIO Platform which offers pneumatic/hydraulic sensing and actuation with positive and negative pressures, while its expansion modules offer additional capabilities, such as electromagnetic actuation for driving vibrotactors.

3 RELATED WORK

This work builds upon prior research in wearable haptic systems, haptic actuators, hardware development platforms, modular and reconfigurable toolkits, and digital knitting.

3.1 Haptic Platforms

Haptic design/development platforms enable experts to test and prototype new user experiences rapidly, and nonexperts to be exposed to haptic technologies with low entry barriers. Many haptic platforms are open-source and made in the form of toolkits. *Hapkit* [29] is an open-hardware kinesthetic haptic device providing hands-on lab experience for online haptic education. *TECHTILE toolkit* [27] is a prototyping tool for record and replay of haptic experiences. *AirTap* [41, 43], a multimodal platform with 16 toroidal vortex generators, enables creating immersive user experiences combining haptic, visual, and auditory feedback. *Touchibo* [12], a texture-changing platform, can enrich communication in group activities through touch. *HAPTICTOUCH Toolkit* [20] renders haptic behaviors such as softness and oscillation using a movable vertical rod. *Compressables* [7] serves as an open-source toolkit for compression-based haptic feedback using soft inflatable structures. *Haptic enchanters* [34] is a platform with attachable vibrotactile haptic modules. *Anisma* [26] is a software and hardware toolkit to prototype tactile haptic feedback using shape memory allows (SMAs).

Many researchers have incorporated modularity in their haptic systems, and few have also explored reconfigurability. In *OmniFiber* [15] Afsar et al. demonstrated how their robotic fibers can be assembled into different structures and configurations to achieve various application possibilities. *TactorBots* [48] offers a modular haptic design toolkit with compact servo-driven modules for the forearm and a web-based authoring tool. *Force Jacket* [4] uses multiple pneumatic bladder modules to render programmable haptic feedback in a jacket. *PneuMod* [46] incorporates localized pressure and thermal feedback using a modular haptic device for social interactions and gaming experiences.

Table 1 presents an abbreviated list of haptic platforms and toolkits. However, the platforms we found are constrained to use a very specific set of haptic primitives operating only with their own actuation systems. They use custom actuators, and are neither compatible nor interoperable with actuators from other systems. Moreover, it is not possible to take components from one of the aforementioned systems and directly use them in another without major redesign. But what if we had a way of combining various different families of actuators with very minimal modification? And what if we were also able to use already existing actuation control systems? This is what our approach aims to achieve. Our platform is modular and fully reconfigurable in the design, prototyping, and interaction phase, where we adapt the haptic platform concept and expand it across different actuation technologies and multiple families of actuators to enable cross-device interoperability, lower barriers to collaboration, and ad-hoc functionalities.

3.2 Actuation Technologies for Haptics

Some of the most prevalent actuation methods for haptic applications are electromechanic (motors and servos) [25], piezoelectric [39], and electromagnetic [35]. For example, *hBracelet* [25] uses four servo motors and one linear actuator to render distributed mechanotactile stimulation on the upper limb. Sauvet et al. used a piezoelectric actuator to generate the haptic illusion of an external force [39]. *Magtics* [35] is a flexible wearable interface for localized tactile feedback.

To improve the rigidity and conformability of these actuators, researchers have also investigated conformable and soft electroactive actuators for on-body haptic interfaces. Among those, SMAs have attracted intense attention in the field. Their fiber-like form factor enables them to be integrated with textiles in many ways. Muthukumarana et al. [30] have stitched SMA wires to fabrics to create skin shear sensations that emulate touch gestures. Seamless seams [31] uses SMAs sewn into fabrics for interactive actuation. *Patch-o* [19] advanced the integration techniques further by weaving SMA wires into patches for on-body actuation. Other advancements in soft haptic actuators include soft magnetic patches on objects that could be activated by on-body voice-coils [24] and electrostatic Hasel actuators [28] for haptic feedback on the palm [40].

Recently, pneumatic and hydraulic actuators have attracted considerable attention for use in wearable haptic devices due to their intrinsic compliance, power density, and reduced electrical risks when used as on-body interfaces. Pneumatic actuators have been used in serial to create lateral motion illusions on the forearm [44], and in parallel on the wrist to generate haptic guidance cues [38].

Haptic projects have been developed based on nearly every actuation technology available, however, we rarely see projects that integrate multiple actuation technologies working together. For instance, fluidic actuators are well suited for high forces and displacement but operate at low frequencies, while vibrotactors offer high frequencies but low forces and displacement. Thus, combining those two technologies would enable high frequencies, forces, and displacement as an example. *SleeveIO* offers the ability of combine multiple types of actuation technologies to enable a large design space for haptic rendering by incorporating fluidic and electric actuation technologies working together.

3.3 Digital Knitting in Actuation Technologies

Machine knitting in the actuator fabrication further advanced the integration of flexible actuators with textiles. Researchers have demonstrated functional textiles knitted with SMAs for a variety of wearable applications, such as for topographically self-fitting wearables [9], tactile on-body interfaces [16], and a hand edema mobilization device [18].

Besides SMAs, machine knitting can also be used with other fiber-like actuators such as cable tendons [2]. Digital knitting also offers custom mechanical properties of the textiles that could be used for pneumatic actuators. Kim et al. machine knitted mechanically anisotropic textiles in extension actuators and scale substrates for locomotion [17]. Luo et al. created bending pneumatic actuators with integrated sensing by machine knitting [23]. In our work, we leverage digital knitting in the creation of custom passive sleeve and band substrates to allow easy attachment and detachment of magnetic couplings.

Table 1: Abbreviated list of haptic development platforms, toolkits, and related technologies and how they compare. SleeveIO supports the most diverse set of actuator types and actuation methods while also being modular and fully reconfigurable.

Project Name	Modular	Reconfigurable	Actuator Types	Actuation Methods	Form Factor
SleeveIO (This work)	Yes	Yes	Vibrotactors Bellows Muscles Suction cups Air-puffing cups Quad-Chamber	Pneumatic Electromagnetic Hydraulic-capable	Soft & Conformable Wearable Battery-powered Untethered
TactorBots [48]	Yes	Yes (Partially)	Servo Motors (Stroke, Rub, Shake, Squeeze, Pat, Tap, Push)	Electro-Mechanical	Rigid Wearable Battery-powered Untethered
OmniFiber [15]	Yes	Yes	Muscles	Pneumatic Hydraulic-capable	Soft & flexible Wearable
AirTap [41]	Yes	No	Vortex Generators	Electromagnetic	Rigid Display-mounted
TECHTILE toolkit [27]	No	No	Voice coil vibrators	Electromagnetic	Rigid Tethered Attaches to objects
Stereohaptics [13]	Yes (Limited)	Yes	Speakers & Subwoofers (Vibration)	Electromagnetic Electrical-capable	Rigid Untethered Wearable
HapticTouch toolkit [20]	No	No	Servo Motor	Electro-Mechanical	Rigid Graspable Battery-operated
Compressables [7]	Partially	Yes (Partially)	Bladders (Compression, Vibration)	Pneumatic	Flexible Wearable Tethered
Hapkit [29]	No	No	DC Motor	Electromechanical	Rigid Tabletop
Haptic Enhancers [34]	Yes	Yes	Vibrotactors (ERM, LRA, Piezo, Voice-Coil Resonator)	Electromagnetic	Rigid Add-ons to objects
Anisma [26]	Yes (1 type)	Yes	Shape-memory alloy	Electrical	On-skin adhesive Wearable
Force Jacket [4]	Yes (1 type)	Yes	Bladders	Pneumatic	Soft Wearable Tethered
PneuMod [47]	Yes	Yes	Silicone bladders Peltier modules	Thermal Pneumatic	Wearable Tethered

3.4 Multimodal Haptic Actuators

Common haptic actuations include vibration [34], pressure [7], suction [14], skin stretch [11], and thermal actuation [8]. Other haptic stimulation methods include chemical haptics and electrical muscle stimulation (EMS) [22, 37]. Recently, researchers have produced multimodal haptic actuators [36, 51], which are capable of rendering multiple types of haptic feedback. Pezent et al. realized squeeze through a servo and vibrotactile feedback using vibrotactors in *Tasbi* [36]. Delazio et al. [4] and Young et al. [45] delivered pressure and vibration through array of pneumatically-actuated air-structures. Zhu et al. combined squeeze, skin stretch, and vibrotactile feedback in *PneuSleeve* [51] using one type of actuator, the Fluidic Fabric Muscle Sheet actuators [50]. Researchers have also explored thermal haptic feedback through the use of Peltier modules [32] and hot and cool fluids [21]. Thermal actuators such as SMAs have the potential to deliver both mechanotactile feedback and thermal haptic feedback. For example, Papadopoulou et al. leveraged the warmth and compression generated by SMAs to promote calmness in an affective sleeve [33].

Having one actuator delivering multiple haptic stimuli is desirable but challenging. We found at maximum three stimuli types achieved by a single modality in the literature [1, 51]. We aim to address this gap by creating a modular platform that supports different types of actuators.

4 SLEEVEIO PLATFORM — OVERVIEW

SleeveIO is a fully-modular and reconfigurable wearable platform for rapid prototyping and testing of multimodal haptic feedback interactions. SleeveIO features five part categories (Figure 2):

Knitted Substrates in sleeve and band form-factors with mesh-like hole patterns for haptic module attachment.

Magnetic Couplings consisting of 3D printed Caps and Poles with integrated magnets offering a quick and easy method for attachment and detachment of different modules to the knitted substrates. The Poles can be inserted through the mesh holes of the substrate and serve as anchor points for module attachment.

Haptic Feedback Modules of different types, behaviors, and actuation approaches, yet all compatible with the Cap & Pole magnetic connection mechanism. Modules of five types have been developed powered by pneumatic and electromagnetic actuation approaches.

Control Hardware to provide actuation and sensing of all the modules. We are using the FlowIO Platform with several of its expansion modules to offer multiple types of actuation.

Control Software for programming the behaviors of the connected modules and for delivering different kinds of user experiences. The FlowIO software stack is used, which offers APIs for Arduino and JavaScript programming as well as a Graphical User Interface with task scheduling options.

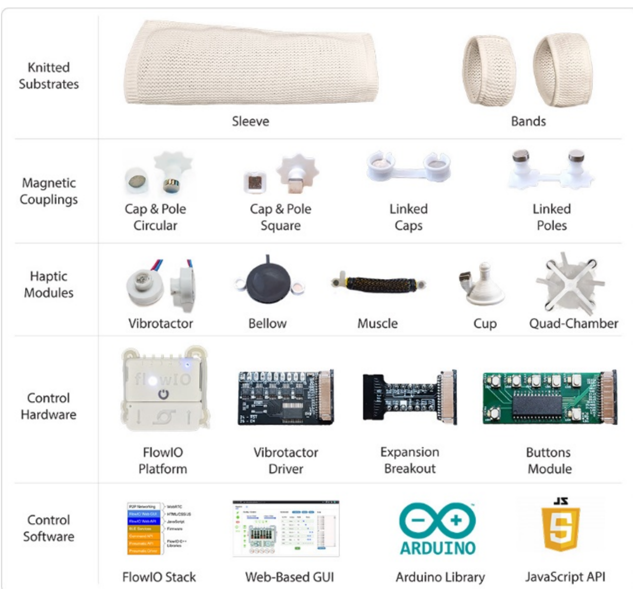


Figure 2: The complete SleeveIO toolkit consisting of Knitted Substrates, Magnetic Couplings, Plug-and-Play Modules, Control Hardware, Control Software with APIs and a GUI.

SleeveIO is entirely self-contained and requires no external hardware or software components, nor any external pressure or power sources. The system is fully wearable, battery-powered, and untethered. The small size makes it possible to transport and store SleeveIO in a mini backpack or a purse, to deploy it on-the-go, and to recharge it anywhere via a micro-USB port. This makes it possible for developers and designers to work with the toolkit from home, on-the-go, or outdoors; they don't have to be confined to a lab setting. The same applies for end-users or user study participants.

While SleeveIO currently has 5 kinds of haptic modules, it is open-ended and allowing new kinds of modules to be created by anyone, simply by adapting haptic feedback actuators from prior works with the SleeveIO magnetic connectors.

In the following sections we are going to discuss in detail each of the components comprising SleeveIO. Moreover, at https://softrobotics.io/sleeveio, readers can find a repository of additional technical details and downloadable resources for replicating and extending this work.

The modules can be connected in many different locations, combinations, and configurations on the knitted substrate. In this way, the structure and function of SleeveIO can be rapidly changed by researchers, interaction designers, and even by end-users.

5 KNITTED SUBSTRATES

Two types of machine-knitted substrates were created for use of SleeveIO on the forearm: (a) a sleeve that covers the entire forearm, and (b) a set of bands offering partial skin coverage and allowing repositioning anywhere along the forearm. The pair of bands was designed for use with modules requiring direct skin contact. By contrast, with the sleeve, actuators transmit haptic forces indirectly - through either the coupling poles or the substrate fabric itself.

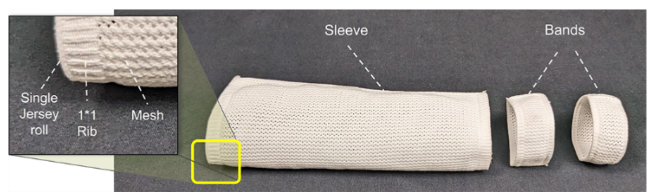


Figure 3: Two kinds of knitted substrates for SleeveIO. Three distinct knit patterns are used in both types of substrates – Pointelle (mesh) in the center region, 1x1 Rib near the edges, and a Single-Jersey roll at the ends to prevent curling.

5.1 Design Choice: Fabric-Based substrate

The substrate's main function is to provide a soft and conformable wearable layer on which the haptic actuators of the SleeveIO system can be securely mounted. We chose a fabric-based substrate not only for its softness, lightweight, and ease of fabrication, but also because as humans we are habituated to the sensation of fabrics touching our skin which makes us to rarely even notice the garments we wear when they fit well. Our aim was to create a substrate that would make SleeveIO nearly imperceptible when idle, and to provide the wearer with an experience similar to that of wearing an ordinary garment. Another reason for our choice is that we envision in the future using this approach as a way of adding haptic feedback capabilities to regular clothes.

5.2 Design Choice: Manufacturing Process

We considered several kinds of fabric-based approaches for creating the substrates, including machine knitting, weaving, and sewing. We chose CNC *machine knitting*, however, because it offered the maximum versatility, stretchability, and design-parameter control compared to any other fabric manufacturing process. We ruled out *weaving* because it offers more limited stretchability and we didn't have access to weaving machines. *Sewing* was an option that was initially of strong interest to us because it is easily accessible to many people and doesn't require advanced expertise. However, the sewing approach requires that a suitable type of fabric be found first which proved to be challenging, and we abandoned that pursuit.

Recommendations for Replicating the SleeveIO Substrates: Although we chose CNC machine knitting for our substrates, we recommend those interested in replicating or extending this work to use sewing manufacturing approach, if they can find suitable mesh fabric. Sewing would be much faster, easier, and far more accessible, and could even be done by hand without a sewing machine. Another accessible option is to try hand-knitting the fabric substrates.

5.3 Design Choice: Hole Pattern and Knitting

We explored several types of hole patterns. First, we tried designs with rectangular and hexagonal pattern of holes spaced 10mm apart. Maintaining a fixed separation between holes proved to be a challenge because the sleeve stretches by different amounts on different regions of the forearm and on different users. Later, we identified a better solution by knitting the substrate as a mesh with densely-spaced holes, enabling poles to be inserted anywhere on the substrate.

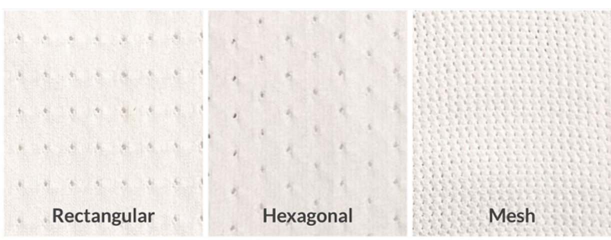


Figure 4: Three types of hole patterns we tried. The mesh hole size has approximately 1 mm diameter, and the separation between holes is 1 mm in the longitudinal and 2mm in the transverse direction. The mesh has 63 courses per inch and 22 wales per inch and is made of yarn type 70d elastane double covered with 1/70/34 nylon.

The sleeve was designed to conform to the shape of the forearm, with the side near the front being tapered. The direction of knitting was from the tapered end toward the wider end, and the tapering was achieved by progressively increasing the number of machine needles involved in the knitting operation. To accommodate different body sizes, we created three sleeves of width size small, medium, and large.

The substrates were knitted on a ShimaSeiki Mach2XS WholeGarment® 4-bed CNC knitting machine using SlideNeedle™ with a gauge of 15 needles per inch. The pointelle mesh was created using the loop transfer operation on the machine. Knitting time is approximately 15 minutes for a sleeve and 4 minutes for a band. The mesh-based sleeve has stretchability of 50% in the longitudinal and 100% in the transverse direction as demonstrated on Figure 5.

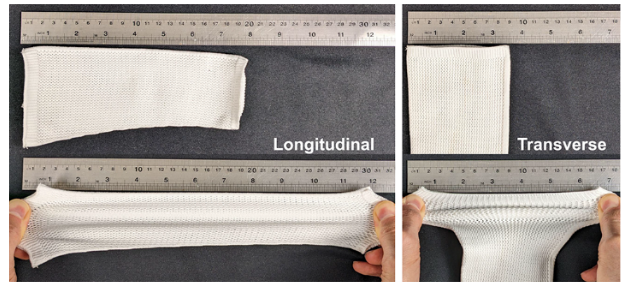


Figure 5: Demonstrating the sleeve's stretchability in the longitudinal (50%) and the transverse (100%) directions.

5.4 Substrate Design Challenges

Some of the challenges we overcame over multiple iterations included finding appropriate level of stretchability, eliminating the tendency of the ends to curl, making the sleeve design conformable to the shape of the arm to provide uniform pressure distribution, and selecting the type and locations of the holes. We also had to properly engineer the tapering profile to ensure uniform coupling to the human skin with uniform stretchability, as well as decide how many sleeve sizes we need and how big each of them should be. Overcoming these and other design challenges required several months and over 15 iterations with incremental changes and improvements. A faster iteration time could be possible with sewing as an alternative to machine knitting.

6 MAGNETIC COUPLINGS

To enable interoperability across many types of haptic actuators and to provide plug-and-play reconfigurability of various haptic modules, we designed a *cap & pole* magnetic attachment mechanism. Our attachment mechanism is one of the primary contributions of this work - offering a universal interface suitable for dozens of new and existing haptic actuators from prior works, enabling interoperability between otherwise-incompatible projects by making them plug-and-play compatible. Several of the modules we developed for SleeveIO, were in fact directly borrowed from prior works and simply adapted with minimal modifications to use our unified magnetic interface, demonstrating how it can apply nearly universally.

6.1 Cap & Pole Interface Design

We designed two versions of cap & pole pairs – a version with a circular magnet and another with a square magnet (Figure 6). The circular version offers rotational freedom while the square version constrains rotation. The circular version is desirable for modules that are attached to at least two connection points (e.g. muscles, bellows) while the square version is most applicable for haptic modules connected to only one point (e.g. suction cups).

In addition to individual caps and poles, we also designed caps and poles that are linked together via a semiflexible 3D printed member. The linked caps and poles enable a single haptic actuator to act over a larger region or to transfer a signal to another pole via the linkage. Moreover, the linked versions can also be used in applications requiring greater structural stability to prevent pole rotation or tilting.

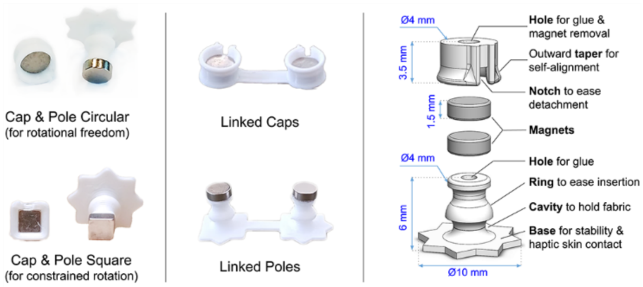


Figure 6: Magnetic Cap and Pole interface design and depiction of the circular, square, and linked versions. The pole had to be as thin as possible to fit through the holes of the sleeve mesh.

Magnetic Poles

The magnetic poles serve two distinct purposes: (1) as anchors to which any actuator module can connect and (2) as a skin interface to transmit haptic forces produced by those modules that don't require direct skin contact. For example, in the case of the suction module and the bellow module, a pole serves only as an attachment point. But in the case of the vibrotactor module, a pole serves the dual role of an *anchor point* for the tactor and a *carrier* of the vibration signal from the tactor to the skin. Figure 7 list all the different ways in which a pole can be used as an anchor and a signal carrier. With appropriate actuator types attached to a pole, it can deliver the sensations of shear, push, rotation, vibration, and angular tilt or precession.

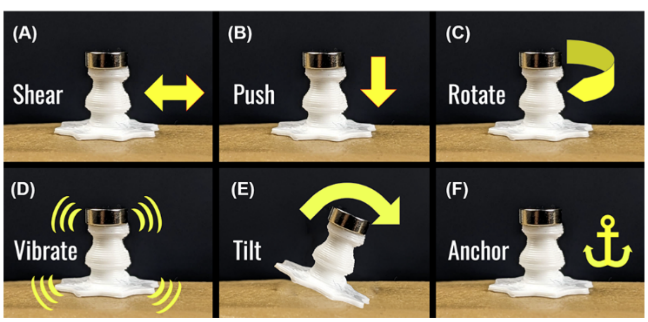


Figure 7: Capabilities of functions possible with a pole alone.

When a pole is used not only as an anchor point but also as a signal carrier, the base of the pole is of vital importance because that is the only part of the pole in contact with the user's skin. Thus, we needed to engineer the base of our pole in such as way as to be able to deliver all the different stimuli depicted in Figure 7, while also being as thin, unobtrusive, and unnoticeable as possible when not being actuated. We tried over 35 base design versions of various shapes, topological features, diameters, and thicknesses to find one capable of providing all desired capabilities in as small form factor as possible; and that was an 8-point shar-shaped base, 0.2mm thick with 10mm diameter – visible in Figure 6.

Magnetic Caps

The cap design has many intricate features, depicted in Figure 6, to make the process of attaching and detaching a cap to a pole possible from a very wide range of angles, to help with self-alignment, and to provide a secure holding force that prevents sliding. The upper section of the cap, where the embedded magnet is sitting, has an inward draft which keeps the magnet secure in place. The lower part has an outward draft to allow connection from angles as wide as 90 degrees. The lower part also has a notch cutout for flexibility of the plastic which makes the disconnect process easier. Finally, at the center of the cap, there is a 2mm diameter hole whose primary role is to allow removal of the magnet in case it is inserted in the wrong orientation. The hole also helps create a better adhesion when gluing the magnet inside the cap.

6.2 Characteristics of the Cap & Pole Interface

Compared to other mechanical attachment methods such as fasteners, Velcro straps, sewing, and snap buttons, this approach offers several advantages including auto-snapping from a distance of a couple centimeters, self-alignment, relatively strong hold, arbitrary placement on the sleeve mesh, easy attachment and detachment of modules, and quick reconfigurability. The holding force of a pair of two poles & caps is approximately identical to the force of lifting a typical smartphone. And since most of the SleeveIO modules connect at two points, disconnecting a module requires nearly the same effort as lifting a smartphone from a table.

To make SleeveIO highly accessible, easy to replicate, and very low cost, we specifically designed our cap & pole interface to be 3D printable on low-cost 3D printers with PLA filament (we used Ender V3). The 3D printable design files and replication details are provided on the project's website, https://softrobotics.io/sleeveio, as well as part numbers for the magnets, glue, and recommended tools. To make the cap & pole connectors durable on any printer and with high tensile strength, we set the infill to 100%, increased the number of shells to 10, and lowered the print speed.

To accommodate different types of actuators that need to be at different distance from the user's skin we have poles of two different lengths. To ensure that a pole stays in place after being inserted through the mesh, we designed the pole with a barbed ring that eases insertion and impedes removal.

7 HAPTIC ACTUATOR MODULES

Wearable haptic devices can be actuated by different actuation approaches such as electromagnetic, pneumatic, hydraulic, electrostatic, and thermal. Moreover, different types of haptic rendering strategies can be employed to generate various haptic sensations such as shear, rotation, precession, vibration, compression, temperature change, and others. We made a set of five distinct haptic actuator modules chosen from or inspired by prior haptic works and made compatible with the SleeveIO platform by augmenting each actuator type with our magnetic cap & pole connector interface. These actuator modules demonstrate three levels of design readiness for the users:

Commercially available actuators – Vibration is one of the most ubiquitous haptic feedback modalities that can be generated using electromagnetic vibrotactor actuators. Among the SleeveIO haptic actuator types, vibrotactors are easily procurable and require only a basic 3D printed housing for compatibility with SleeveIO.

Existing designs from the literature – SleeveIO enables researchers and designers to take proposed haptic actuators from the literature and, with minimal or no modifications to the original fabrication process, make them compatible with SleeveIO and interoperable with other types of haptic actuators from the literature. To demonstrate this process, we created three types of dissimilar haptic modules for SleeveIO (bellows, muscles, and cup-type actuators) simply by replicating prior works (Bellowband [45], McKibben muscles [6], and SkinBot [5], respectively) and adding to them our cap & pole magnetic connectors. This process can be applied to make compatible with SleeveIO numerous other actuators from the haptics literature [49] including with Pneumatic, Hydraulic, Electromagnetic, Electromechanical, and Thermal actuation.

Novel designs – To demonstrate the viability of designing and fabricating novel haptic actuators compatible with SleeveIO's magnetic attachment method, we designed a simple yet novel haptic actuator module not based on prior works. We call it a "Quad-chamber actuator" since it provides force in four lateral directions. This demonstrates how even new actuator types that may be developed in the future by the haptics community can also be easily made compatible with SleeveIO and combined with prior works.

7.1 Vibrotactor Modules

We chose the Mini Motor Disk 1201 from Adafruit as a basis for our vibrotactor module. Compared to all other SleeveIO modules, the vibrotactor module was the simplest to design in terms of effort, and it consists of a disk motor, a 3D printed housing around it, and a magnetic cap glued to the bottom of the housing to make it compatible with SleeveIO's magnetic poles. As shown in Figure 8, the vibrotactor housing can be designed so that it attaches to one pole using a single cap or to multiple poles using linked caps if vibration over a larger area is desirable.

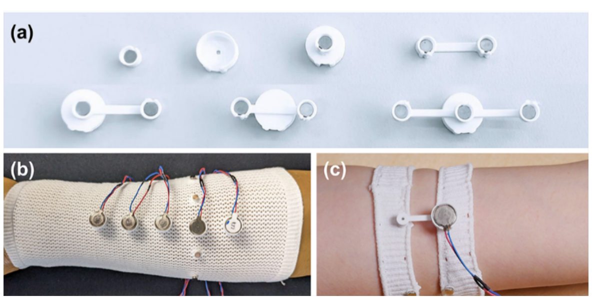


Figure 8: (a) Vibrotactor housings with one, two, or three linked magnetic caps. Attachment of vibrotactor modules to the magnetic poles on the (b) sleeve and (c) band knitted substrates.

7.2 Bellow Modules

By following the design and manufacturing process described in Bellowband [45], we created bellow modules with two and three chambers using heat pressing of thermoplastic polyurethane (TPU) films. Bellow modules can render compression and tap stimuli. Making the bellows compatible with the SleeveIO cap & pole coupling approach required designing a suitable connector for the bellow.

Conceiving and designing such a magnetic connector was a major challenge because of the requirements it had to meet. It had to: (1) hold the bellow centered between two poles, (2) at an angle normal to the skin surface; (3) be flexible to follow the arm's curvature, (4) yet rigid enough to not let the bellow disconnect; (5) offer stretchability to accommodate variable separation between poles when the sleeve stretches; and (6) be 3D printed, inexpensive, and easy to replicate by anyone. Meeting these objectives took many design iterations and trials some of which as shown on Figure 9.

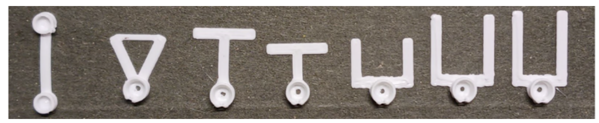


Figure 9: Initial design iterations of the bellow connector.

Ultimately, we identified a solution, indicated on Figure 10, by creating two 3D printed structures with a magnetic cap on one end and a horseshoe type of bifurcation on the other end. The connectors slide between the first chamber and the backing of a bellow, with two of them placed on opposite sides. The structure is only 0.2mm thin to offer flexibility, while the horseshoe design ensures that the bellow remains grasped firmly and remains normal to the skin; it also allows for variability in the separation distance between the two to accommodate sleeve stretchability up to 1cm.

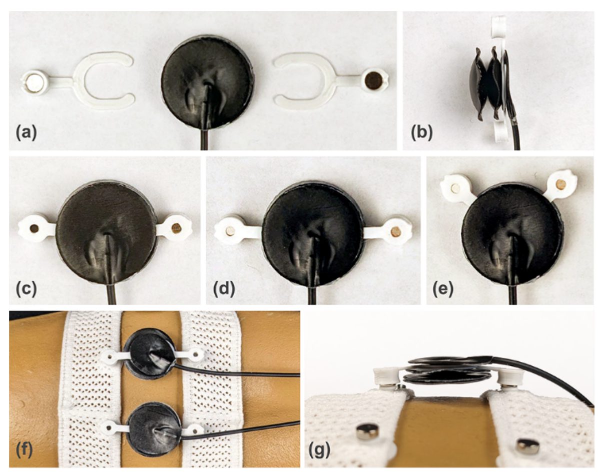


Figure 10: (a) Magnetic connector for the bellow module. It holds the module in place and self-adjusts the connector if the location of the poles changes as a result sleeve stretch. (b) Inflated state of the bellow. (c, d, e) Demonstration of motion flexibility of the connectors. (f, g) Bellow modules attached to two knitted bands. Skin contact occurs only during actuation.

Our bellows are identical to those in [45], where readers can find their mechanical characteristics. The only difference in our work is the attachment mechanism, having the added benefit of no skin contact during the unactuated phase.

7.3 Muscle Modules

Muscle actuators contract when pressurized, extend when depressurized, and render tangential skin shear transferred between two anchoring magnetic poles. In a radial configuration, they can also exert squeeze forces on the forearm. Muscles are relatively easy to make with only a few basic materials – braided sleeve, balloon, string, glue, a plug, and a pneumatic coupling. They can be made of different diameters and lengths. We adopted the design and manufacturing process for our muscle actuators from [6]. To make the muscles compatible with SleeveIO's poles, we designed two custom couplers with magnetic caps that go on the two sides of the muscle as pictured in Figure 10a. One is simply a plug and the other one serves as an air inlet/outlet. The latter one presented a significant design challenge because it had to contain a magnetic cap on the outside, an air channel on the inside, while being sturdy and durable. Meeting these criteria also required that a Form 3 printer be used. Another challenge when creating this type of module was ensuring perfect rotational alignment between the magnetic couplings on the two sides during assembly. Assembly details are provided on the project's website.

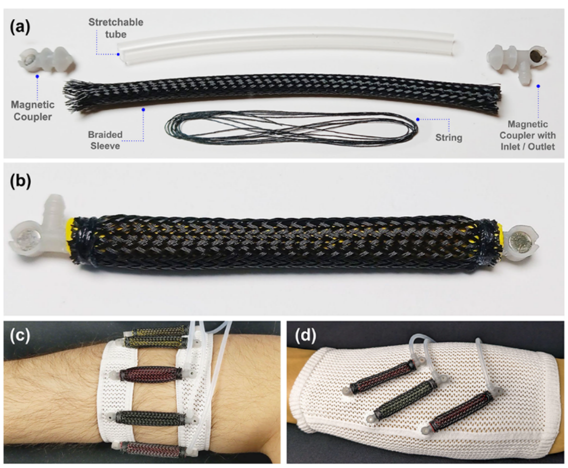


Figure 11: A muscle module (a) before assembly and (b) after assembly. (c, d) The modules can be attached to the sleeve in any orientation or configuration.

7.4 Cup Modules – Suction and Puff

The cup module of SleeveIO is inspired by the SkinBot project [5], a small robot capable of walking directly on a user's skin using small pneumatic suction cups. We took the suction cup design from SkinBot, modified it to be compatible with our cap & pole attachment approach, and repurposed it to be used as a haptic feedback actuator. Moreover, we also realized that this actuator can be used not only for providing suction stimuli but also for delivering a puff of air to the user when connected to a pneumatic control system capable of both vacuum and positive pressure, such as the FlowIO Platform. Thus, the same cup module serves as a dual-action - suction and puff - actuator.

Some of the challenges we faced included finding a way to attach the cup to the SleeveIO poles, optimizing the distance to the magnet for stability yet sufficient clearance, selecting appropriate wall thickness and height, and optimizing for printability on any inexpensive desktop 3D printer. Figure 12 shows a few of the various early versions designed and tested before arriving at an optimal solution shown in Figure 13.

Figure 12: Early iterations of the dual-action cup module.

Unlike the other modules which have an integrated female coupling (cap), this module was better suited for an integrated male coupling (pole), to connect it between two anchoring poles via linked caps. Figure 13 shows details of our final design, which uses the square rather than circular coupling to constrain any rotation. It was printed on the low-cost Ender V3 printer.

In addition to suction and puff stimuli, this actuator would also be suitable for providing pull, drag, and precession stimuli. However, enabling these possibilities would require additional hardware to be developed around the cup actuator, which we leave for future work.

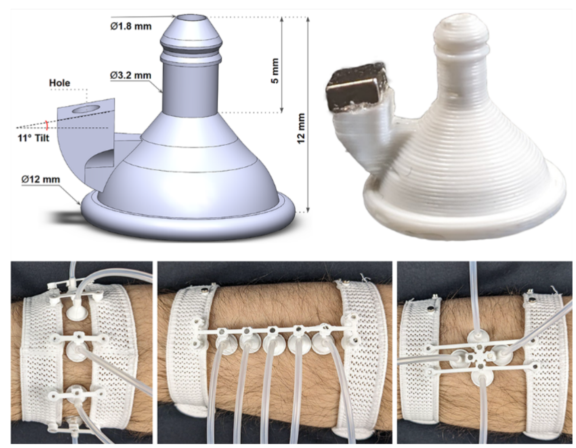


Figure 13: (a) Design model of the dual-action cup actuator. (b) 3D printed module with square magnetic connector. (c) The module can be attached in various configurations and combinations using different kinds of linked caps.

7.5 Quad-Chamber Modules

To leverage the unique properties of the SleeveIO cap & pole hardware architecture we created a novel but simple actuation module which we call Quad-Chamber because it has four air-chambers. This module is placed in the middle between four poles, and is then able to push or vibrate any one of those four poles, as shown in Figure 14c. When it pushes on a pole, it causes the pole to change its angle, causing the user to feel part of the base's edge. This is especially effective with the star-shaped pole base because the corners of the star provide a stronger haptic stimulus when angled toward the skin. Nevertheless, despite the pointy edges, they do not cause any pain to the user.

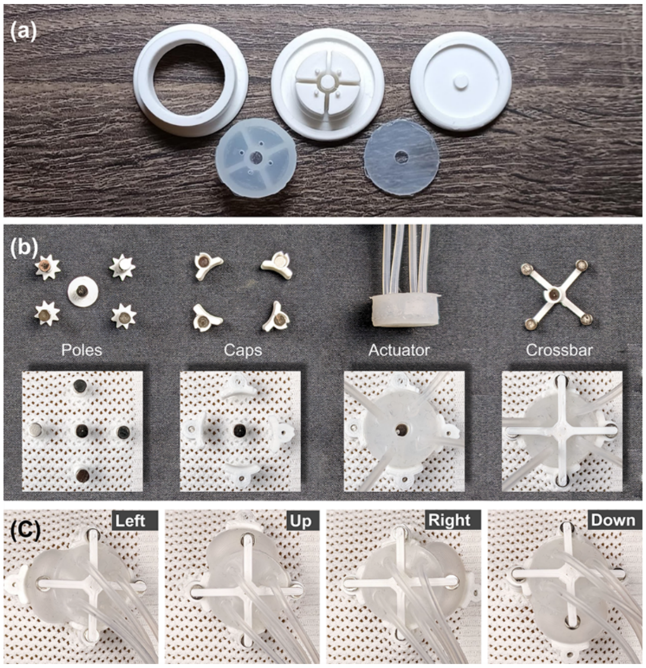


Figure 14: (a) 3D printed mold and silicone casts of the quad-chamber actuator. (b) Components of the module and attachment sequence. (c) Sequential actuation of all four chambers, one at a time.

The Quad-Chamber module consists of a silicone actuator with 4 chambers (casted out of Ecoflex 30 using a 3D printed mold - Figure 14a), four magnetic caps onto which each chamber pushes when pressurized, and a magnetic crossbar that holds the chamber and provides magnetic restoring force after a chamber is depressurized – Figure 14b. We created two sizes of this module with different diameters for users of different arm widths, though our pilot study later showed that only a small-diameter version suffices for all.

There are multiple actuation patterns possible with the quad-chamber module, especially considering the various combinations of chambers and sequences of actuation of each chamber. When a single chamber is actuated once, it can provide directional information to a user such as left, right, up, down. Or for a more salient experience, a chamber can be actuated repeatedly to cause a vibrational sensation. When two chambers are used, they can provide linear information to a user such as horizontal, vertical, diagonal northeast, and diagonal northwest. When all four chambers are used, they can deliver rotational information such as clockwise and counterclockwise, Figure 15. Navigational guidance would be a well-suited application for this module.

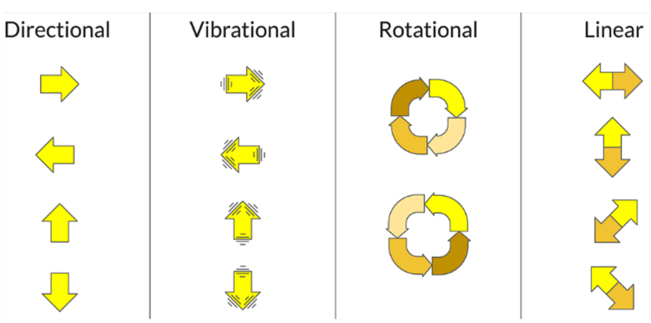


Figure 15: Actuation Behaviors of a Quad-Chamber module.

8 CONTROL HARDWARE AND SOFTWARE

To control the different modules of SleeveIO, we needed a pneumatic control device capable of delivering positive pressures, negative pressures, and to have the ability to monitor the pressure continuously. We also needed a controller for our vibrotactile modules. Moreover, to make SleeveIO fully wearable and untethered, we wanted the control hardware itself to be small and wearable, battery-powered, and to support actuation approaches beyond pneumatics for other types of modules that may be added to SleeveIO in the future such as thermal and electromechanical haptic modules. And ideally, the controller had to be inexpensive and easy to procure or replicate so that this work is accessible to as many people as possible. The FlowIO Platform [24] was the only controller that met all our objectives. Nevertheless, other pneumatic and electronic control systems can also be used for actuation of SleeveIO, especially if wearability, size, portability, or cost are not of important significance to the user or researcher / designer.

FlowIO Platform is a miniaturized wearable tool primarily for pneumatic actuation and sensing with Bluetooth capabilities and five programmable pneumatic ports, each capable of inflation, vacuum, pressure release, pressure sense, and flow-rate-variability. However, FlowIO also features a set of expansion board that extend its capabilities which make it capable of offering hydraulic, electromagnetic, electromechanical, and thermal actuation in addition to pneumatic actuation. For actuation of the vibrotactile module, we use the *FlowIO Vibrotactor Driver Board*, which offers an integrated library of 123 vibration effects (waveforms) and is capable of driving up to five vibrotactor modules. Other FlowIO expansion boards we leverage in this work include the *Expansion Breakout Board* and the *Buttons Module*, the latter of which provides 7 programmable push buttons and LEDs to which different actuation behaviors or patterns can be mapped and recorded / replayed. All the control hardware we used is shown in Figure 2.

Pressure ranges from -26 psi to +30 psi and flow-rates up to 3.2 L/min can be achieved with FlowIO in different pneumatic configurations. For our bellow modules we used pressures up to 10 psi and up to 10 cycles per second. For the muscles we used approximately 15-20 psi and frequencies up to 5 Hz. For the quad-chamber module we used pressures below 10 psi and frequencies up to 3 Hz. When actuating the dual-action cup modules, we used the maximum pressures of 20 psi and flow-rate of 1.6 L/min for the air-puff stimulus, while for the suction stimulus we used pressures of -15 psi and flow-rate of -1.3 L/min.

Additionally, since FlowIO has a complete stack of user-friendly software capabilities including a graphical user interface (GUI), Arduino libraries, and web-based JavaScript APIs, those features make it possible to control SleeveIO graphically from https://www.softrobotics.io/gui or to create new custom haptic user experiences with only a few lines of C++ or JavaScript code. This makes it possible for researchers, engineers, and designers of any technical background to easily use SleeveIO not only to *feel* haptic experiences, but also to *create* their own multimodal haptic feedback experiences combining multiple types of actuators. While only 5 modules of any kind can be connected to a single FlowIO device, the software and hardware also allow up to 7 FlowIO devices to be used together synchronously, thus enabling user experiences with up to 35 haptic modules.

9 PILOT ASSESSMENTS

We chose to evaluate our system on the basis of whether it is capable of rendering a diverse set of haptic stimuli in a way where the user can perceive them easily and unambiguously. We specifically chose well-known actuators and evaluated some of their perception characteristics to identify whether our modular coupling approach would still produce the perception outcomes expected for those known actuators. We chose to study the localizability, perception accuracy, sensation familiarity, and haptic salience of the haptic modules to demonstrate the basic haptic design space with our system with predefined designs. The goal of our pilot assessments is to demonstrate the diverse and distinguishable haptic feedback possible with SleeveIO. The more types of haptic stimuli a system can generate, the more expressive the system is, and the larger the design space it offers. Validating the *haptic viability and usability* of the SleeveIO platform and each module is a prerequisite for a future longitudinal user study to evaluate the *multimodal possibilities* enabled by SleeveIO's modularity, reconfigurability, and actuator combination capability, where researchers and designers will explore the full design space of SleeveIO on their own accord over an extended time period.

We conducted pilot assessments of SleeveIO with 6 participants (2 females and 4 males between the ages of 23 and 36) testing the system's usability and each module's haptic characteristics in different configurations. We offered three sizes of knitted substrates and asked our participants to choose the size most suitable for them. Each participant was asked to complete a series of activities involving a reconfigurability exploration of SleeveIO, a set of actuation pattern recognition, and subjective assessment of system behaviors. The total time required per participant to complete all activities was approximately two hours.

We chose the separation between actuators and the locations on the body based on preliminary user feedback from the authors who tried many different separations and locations.

9.1 Reconfigurability Exploration

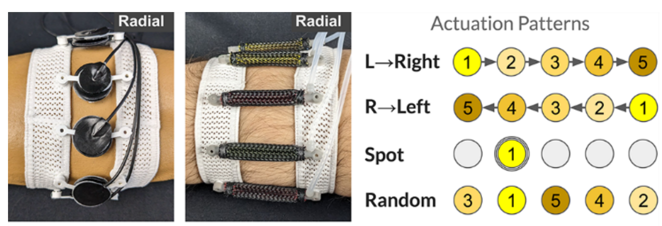
Activity A - Comfort and Reconfiguration

Each participant was provided with a sleeve and 6 poles. They were first asked to put on the bare sleeve then comment on the level of comfort when wearing it for 30 seconds. Afterwards, they were asked to take off the sleeve, insert the six poles through the mesh at arbitrary locations, put the sleeve back on their arm, and comment whether they could feel the presence of any of the poles when their arms were stationary and when moving. All participants reported that the sleeve fits well and is comfortable. The pole-insertion process was successfully completed by all six participants. Everyone reported that they didn't feel the presence of any poles when their arms were stationary, and one person reported feeling some of the poles during arm movement.

9.2 Haptic Pattern Recognition

Activities B & C - Bellow and Muscle Actuators

We placed 5 identical actuator modules radially around a participant's forearm (bellows in activity B, muscle actuators in activity C) with a separation of approximately 2.5cm between actuators; then played one of 4 actuation patterns selected at random and asked the participant to indicate which pattern they felt (Figure 16). We conducted 16 runs of this test with the patterns arranged in a random order. To ensure that users relied only on their sense of touch, we used a visual barrier between their arm and eyes. We allowed participants up to two additional runs of an actuation pattern if they had difficulty identifying it. For the bellows (B), most participants found the sensation pleasant or neutral and said that the linear patterns felt as if something was walking on their arm. They also reported that the linear patterns were easy to identify, while the point pattern and the nonlinear were more difficult. One participant also reported that mental focus was required to be able to differentiate the actuation patterns. For the muscles (C), participants rated the sensation as pleasant. One user commented that this activity was easier than the bellows while another user made the opposite remark. One person described the experience as a light pinch on the arm, while another said that it felt comfortable and that the signals were clearly identifiable.



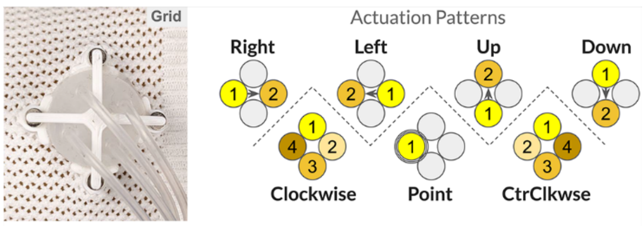
Pattern Recognition Accuracy by Participants

Activity	Config	p1	p2	p3	p4	p5	p6
B. Bellows	Radial	100%	81%	94%	100%	100%	94%
C. Muscles	Radial	100%	94%	100%	100%	100%	100%

Figure 16: Placement of actuators for activities B and C, and actuation patterns tested. Mean recognition accuracy of each participant from activities B and C.

Activity D – Quad-chamber Actuators

We placed a quad-chamber actuator on a user's forearm and rendered 7 different actuation patterns (Figure 17). We conducted 28 runs of this test per user with the patterns arranged in a random order, ensuring that each of the 7 patterns occur 4 times during the 28 runs. Moreover, we ran this test twice to compare quad-chamber actuators of two different diameters (d=20mm and d=25mm) and found that smaller diameter yielded better recognition accuracy on average. Users rated the sensation as weak in terms of strength, and as neutral in terms of how pleasant or unpleasant it was. Several users said that it was difficult to recognize the patterns initially, but recognition became easier after the first few runs. Two users also commented that the circular patterns were easier to recognize than the linear ones.



Pattern Recognition Accuracy by Participants

Activity	Config	p1	p2	p3	p4	p5	p6
D. Chamber S	Grid	79%	50%	46%	93%	61%	39%
D. Chamber L	Grid	36%	54%	43%	89%	71%	54%

Figure 17: (Top) The quad-chamber actuator and the seven actuation patterns used during activity D. (Bottom) Mean recognition accuracy of each participant from activity D.

Activity E – Vibrotactors

To test the pattern recognition accuracy of our vibrotactile modules, we tried three different arrangements on the forearm – radial (similar to activities B and C), grid (similar to activity D), and longitudinal / medial (along the length of the forearm), Figure 18. For radial and medial placements, we used the same patterns and protocol as in activities B & C, while for grid placement – the same as in activity D.

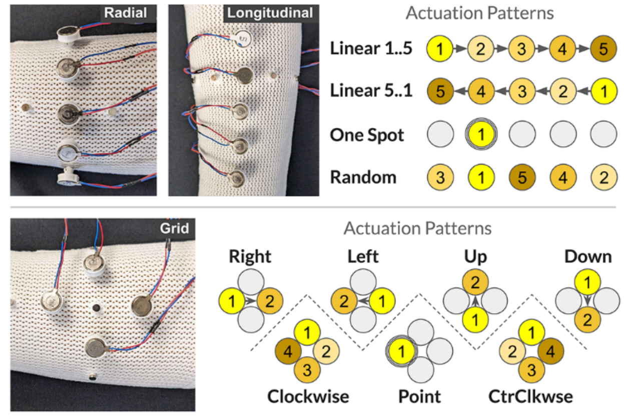
Nearly all users reported being most confident about their answers for the radial configuration and least confident for the grid configuration. Although everyone rated vibration as a very familiar sensation, some users said that they never experienced it on their forearm.

Activities F & G – Cup Module – Suction and Puff Stimuli

Our last two activities were identical in structure to activity E. We first ran the puffing actuator tests in all three configurations, followed by the suction actuator tests. Similar to the comments from activity E, users reported that – in identifying haptic patterns for both puff and suction – the lateral arrangement was the easiest and the grid was the most difficult. All participants said that both the suction and the puff stimuli were the most unfamiliar.

9.3 Subjective Assessment of Actuator Modules

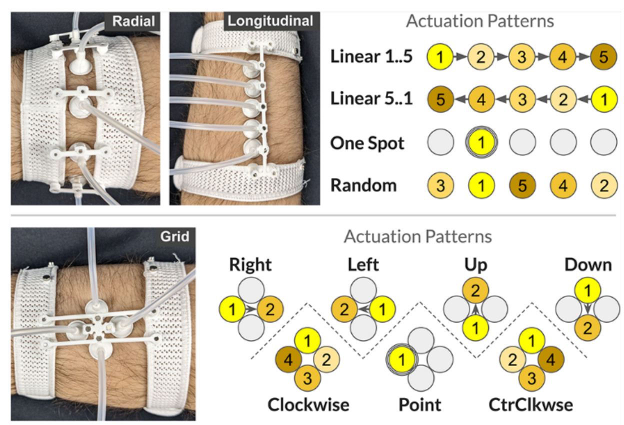
The results from our qualitative studies comparing the different actuator modules are shown in Figure 20. One unexpected finding from our pilot was that users reported needing different levels of concentration to identify haptic patterns for different haptic modules. We did not explicitly ask users to comment on the level of focus demanded by each test, but most left comments. Based on these comments, we can conclude that the suction and muscle actuator modules were the least cognitively demanding, followed by



Pattern Recognition Accuracy by Participants

Activity	Config	p1	p2	p3	p4	p5	p6
E. VTactor	Radial	100%	94%	100%	100%	94%	88%
E. VTactor	Medial	100%	94%	100%	100%	88%	44%
E. VTactor	Grid	100%	82%	93%	89%	100%	71%

Figure 18: Radial, longitudinal, and grid configurations of vibrotactor modules in activity E with corresponding actuation patterns. Pattern recognition accuracy by each participant.



Pattern Recognition Accuracy by Participants

Activity	Config	p1	p2	p3	p4	p5	p6
F. Puff Cup	Radial	100%	88%	88%	100%	88%	100%
F. Puff Cup	Medial	63%	63%	63%	94%	88%	69%
F. Puff Cup	Grid	64%	50%	39%	82%	86%	61%
G. Vac Cup	Radial	88%	100%	81%	100%	100%	81%
G. Vac Cup	Medial	75%	63%	56%	81%	100%	88%
G. Vac Cup	Grid	100%	57%	46%	89%	100%	50%

Figure 19: Radial, longitudinal, and grid configurations of puff and suction actuator modules in activities F and G with corresponding actuation patterns. Pattern recognition accuracy by each participant.

the vibrotactor and bellows requiring a bit more focus, and that the puffer and quad-chamber actuators needed the most concentration. Another surprising finding was that half the users found the magnetic snapping action and the corresponding clicking sound highly satisfying in itself, while the other half found it as an unfavorable characteristic.

Users reported that the muscle actuators delivered the most enjoyable haptic sensations, followed by the puffer and the bellow actuators. Users had mixed feelings regarding the pleasantness of the vibrotactor, quad-chamber, and suction actuators, where some rated them as pleasant and others unpleasant. Several users said that the suction actuator would be suitable for an urgent notification (e.g., hazard alert), and that the muscle, bellow, or puff actuators would be suitable for a subtle reminder (e.g., to feed a pet).

While most participants had significant familiarity and exposure to haptic feedback technologies, nearly all participants reported the stimuli by the suction, puff, and quad-chamber actuators as feeling highly unfamiliar to them.

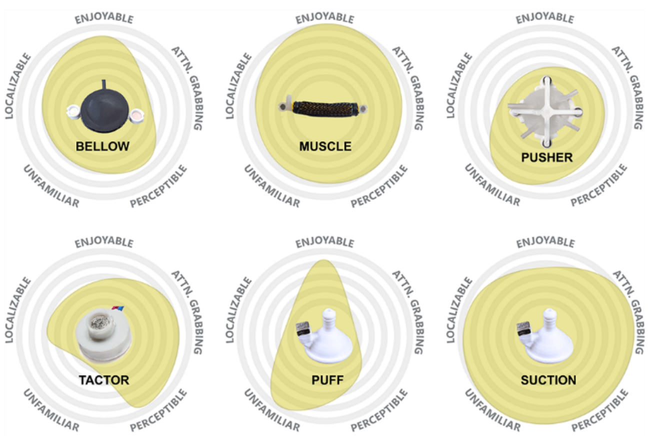


Figure 20: Haptic module qualitative comparisons.

10 APPLICATION POSSIBILITIES

As a wearable haptics system with high expressivity, SleeveIO can be used for countless applications that are commonly discussed in the haptics literature. Examples of those would include: navigation for cyclists; discreet notifications if the SleeveIO is worn underneath a coat; haptic telepresence for shared user experiences through touch; integration with AR / VR to provide more immersive user experiences; gaming augmentation to add touch and more realism in games.

In addition to the those commonly known applications, SleeveIO also unlocks some far more unique use cases and application paradigms, that specifically exploit SleeveIO's more unique features of modularity, reconfigurability, plug-and-play capability, combination of different modules and actuation approaches, user-friendliness with low barriers, and ease of replication. Examples of those would include:

Educational tool – for haptic feedback, interaction design, mechanical engineering, and for creating demonstrations.

Prototyping toolkit – for enabling researchers, engineers, and designers to rapidly develop and test new haptic feedback experiences that incorporate multiple types of actuators.

Haptic Language Interface – that exploits the nearly infinite expressivity of SleeveIO, where the modularity, reconfigurability, and the ability to combine modules of many kinds would allow each alphanumeric character to have its own haptic representation based on instantaneous actuation rather than sequential actuation of the modules.

Transformed Replay – while record-replay is a common application for haptic feedback systems, SleeveIO can play a recorded experience in a transformed way where one or more actuators are swapped with a different type of actuator while keeping their position the same, enabling many variations of the same recorded experiences.

Transformed telepresence – this is similar to Transformed Replay, expect that the input comes not from a recording, but from another device worn by another user. Then the output can be transformed just by a change of actuator type.

Ideation tool – that exploits the modular, reconfigurable, and plug-and-play nature of SleeveIO to help interaction designers come up with new ideas and to test an idea on the spot by just swapping modules, combining them in new ways, or changing the actuation signals on-the-fly.

Personalizable Haptic Interface – that enables end-users to modify and personalize the haptic experience provided by their game by swapping one module type with another or by changing the location of modules.

On-the-go Haptics Lab – the miniature form-factor and the battery-powered Bluetooth controlled nature of the system make it suitable to be carried in a small bag and be deployed and used anywhere. While the wide diversity of hardware components and modules allow it to serve as a portable haptics research lab rather than just a single device.

11 FUTURE WORK

SleeveIO provides a strong foundation for wearable haptic interface research. However, the platform has several limitations and opportunities for further development.

Wearability beyond the forearm - the knitted substrates of SleeveIO today are designed for the forearm, but we can design substrates for other body parts, or even integrate this approach into regular everyday garments.

Richer input - SleeveIO predominantly focuses on haptic output. Development of input modules such as position, orientation, and contact, could further enrich interactions.

Deeper characterization - Our pilot assessment only scratched the surface of determining SleeveIO's capabilities. There remains substantial mechanical, psychophysical, and cognitive characterization of the system. Further, pairing SleeveIO with audio/visual systems (such as augmented reality glasses) creates opportunities in multisensory research.

Application design - Applications for SleeveIO are limited only by the imagination of the interaction designer. Some areas include: notifications, navigation, haptic language design, fashion, telepresence, education, discrete communication, skills training, and many others.

Accessibility - In future work we plan to organize materials, actuator modules, construction methods, interaction tutorials, and so on, in the aim of making SleeveIO accessible to as wide of an audience as is possible.

Modality Experience Study - Although we have demonstrated the modularity of our device by presenting several different configurations from the same modules, we have not studied how users could freely leverage this modularity in their own design process. In the future, we plan to run a study where users design the haptic experiences freely by themselves and learn more about users' feedback on the modularity and reconfigurability of our system.

12 CONCLUSION

Motivated by the problem we face today in haptics of incompatibility between different actuators and systems, we presented an approach for how to make dissimilar projects and actuator types compatible with one another. We demonstrated our approach through a platform we developed called SleeveIO, as a first step toward a future where a variety of dissimilar haptic actuators and actuation approaches can coexist and be rapidly integrated with each other to develop multimodal haptic user experiences with ease. SleeveIO incorporates the high-level characteristics we aimed for of modularity, reconfigurability, multiple actuator types, and multiple actuation approaches.

We described the main components of SleeveIO including: knitted substrates, magnetic couplings, wearable untethered control hardware, and a corresponding control software. We presented five distinct types of modules and how they were all adapted to be compatible with SleeveIO – some of them originating from prior works, while others being novel. We conducted a pilot assessment of the platform to determine its haptic perception viability. We discussed numerous applications in which SleeveIO can be used, leveraging its unique properties, and we presented an array of possible ways of how this project can be extended in the future.

This work was designed specifically for lowering barriers to entry into haptics, to be easy to replicate by anyone with affordable tools and alternative approaches (e.g. sewing), and to enable people from all backgrounds to have access to this work. For this reason, we also provided a project website at https://softorobitcs.io/sleeveio with additional resources.

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