ANISMA: A Prototyping Toolkit to Explore Haptic Skin Deformation Applications Using Shape-Memory Alloys

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We present ANISMA, a software and hardware toolkit to prototype on-skin haptic devices that generate skin deformation stimuli like pressure, stretch, and motion using shape-memory alloys (SMAs). Our toolkit embeds expert knowledge that makes SMA spring actuators more accessible to human–computer interaction (HCI) researchers. Using our software tool, users can design different actuator layouts, program their spatio-temporal actuation and preview the resulting deformation behavior to verify a design at an early stage. Our toolkit allows exporting the actuator layout and 3D printing it directly on skin adhesive. To test different actuation sequences on the skin, a user can connect the SMA actuators to our customized driver board and reprogram them using our visual programming interface. We report a technical analysis, verify the perceptibility of essential ANISMA skin deformation devices with 8 participants, and evaluate ANISMA regarding its usability and supported creativity with 12 HCI researchers in a creative design task.

CCS Concepts: • **Human-centered computing** → *User interface design*; **User interface toolkits**; **Haptic devices;**

Additional Key Words and Phrases: Haptic, tactile, toolkit, authoring, shape-memory alloy, SMA, skin, deformation, design, fabrication, programming, prototyping, software, hardware

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1 INTRODUCTION

The accessibility of emerging technologies is crucial for **human–computer interaction** (**HCI**) researchers to develop new interaction techniques, explore novel applications, and enable an early dialogue between basic and applied sciences on future research directions [5, 59]. However, the technical challenges and expert knowledge required to apply new technologies can form a barrier to explore their use cases [1]. Lately, smart materials like **shape-memory alloys** (**SMAs**) arouse great interest in the area of haptics [4, 6], as they allow to build much more flexible and compact interfaces [11, 27, 38, 76, 78] compared to conventional actuators such as vibration motors, solenoids, and hydraulic pumps.

Actuators made of these materials can easily align with curved body features, allow targeting our sense of touch more effectively, and offer an opportunity to address the increasing demand for wearable haptic devices in mobile computing and virtual reality applications.

Recent work demonstrates that SMA actuators are particularly suited to physically deform the skin because of their large displacement length and high force-to-weight ratio [27, 28, 46]. They depict very thin wires or helical springs that contract silently and exert a strong pulling force when applying power at their ends. Their smooth contraction can invoke skin-deformation stimuli like pressure, stretch, and motion that suit to generate more natural sensations than vibration alone. Researchers have highlighted their potential benefit for various applications, including mediated social touch [66, 77], therapeutic means [15, 40], skill transfer [19, 46, 50], as well as subtle feedback for collaborative mixed reality and immersive virtual reality experiences [45, 49, 50, 62].

However, the adaption of SMA actuators for haptic applications is still at an early stage. Developing skin-deformation devices using SMAs and validating their haptic sensation requires HCI researchers to possess various skills, including programming, fabrication, and electrical engineering. Prior work has proposed different techniques to fabricate skin-deformation devices using SMAs, showed how the actuator's heat can be isolated from the skin, and demonstrated expressive ways of using the actuator's bare pulling force through implementing different end-effectors [27, 46]. Nevertheless, an accurate control, long durability, and easy way to prototype multi SMA devices yet remain challenging tasks that limit the exploration of skin-deformation devices using SMAs.

On one side, hardware toolkits can help overcome technical challenges and reduce the required electrical engineering knowledge [1]. On the other side, software environments can help users explore different ideas by exchanging and comparing parts quickly, safely, and cheaply [63]. They can convey additional knowledge in the world by indicating constraints and limitations, guide the user to effective designs, or even prevent infeasible ones before their physical implementation. Yet, prototyping toolkits and authoring tools that ease the prototyping process with SMAs for skin-deformation applications, similar to those existing for vibration motors [34, 43, 57, 64, 65], are missing.

In this article, we present ANISMA, a first software and hardware prototyping toolkit that aims to simplify the process of designing, programming, testing, and implementing SMA-based skin deformation devices. The toolkit is designed to address many of the challenges that users, particularly HCI researchers, face when working with SMAs for a wearable haptic device. Below, we summarize the main contributions of this work:

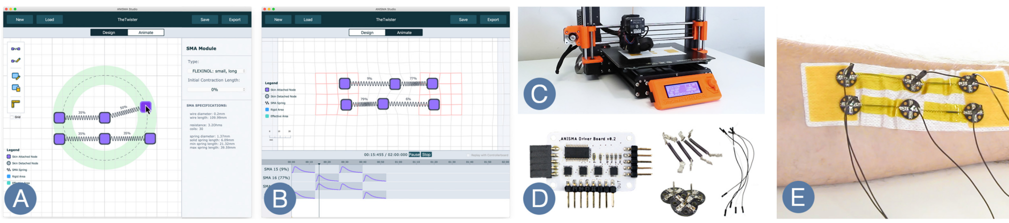


Fig. 1. ANISMA is a prototyping toolkit that supports users from the draft of an initial idea up to the realization of a functional prototype: The user can (a) design an actuator layout; (b) visually program and simulate the actuation behavior to verify the virtual design; (c) export the layout and print it on skin adhesive; (d) assemble the physical prototype using the physical widget kit; and (e) reprogram the device and test the sensation on the skin.

- ANISMA, an end-to-end prototyping toolkit for SMA-based skin deformation devices, which comprises:
  - A software environment to interactively design and animate (simulate) haptic devices. The tool allows users to define a device's layout, specify its actuation sequence, and preview its behavior in a safe environment. The tool can convert a virtual design into a 3D-printable file. It allows visually programming and controlling the physical device.
  - An empirically derived actuation model to control SMAs.
  - A control unit including a customized and programmable driver board that allows connecting and driving multiple SMAs.
  - A reliable method to fabricate and reproduce skin-deformation devices based on a digital blueprint. The SMA actuators are firmly integrated, but remain reusable.
- A synthesis of system requirements based on interviews and a focus group conducted with HCI researches in the field of haptics.
- We made ANISMA software open-source, so that users can freely access our toolkit to design and simulate SMA-based skin-deformation devices. Also, advanced users can extend ANISMA and utilize it for their own needs.

2 BACKGROUND AND RELATED WORK

2.1 On-Body Haptic Feedback Using SMAs

A growing body of work is investigating new techniques to integrate SMAs into wearable interfaces that allow to recreate natural haptic sensations for mediated social touch [15, 66, 77], interpersonal communication [8, 44, 55] and enhanced virtual experiences [45, 50, 58]. In contrast to vibration motors, which are most commonly used for haptic feedback, SMA actuators provide a smooth and silent contraction which can be utilized in order to physically deform the skin. The skin-deformation stimulates mechanoreceptors that are sensitive to pressure (Merkel cells, SA-I) and stretch stimuli (Merkel cells, SA-II) [14]. The resulting sensations can feel more natural than ones induced by vibration only (sensed by Pacinian corpuscle, RA-II) [66]; they, therefore, depict an important complementary feedback modality that can allow to generate even stronger sensations than the vibrotactile on its own [31].

Early approaches using SMAs demonstrated how to invoke mainly squeezing and pressure sensations using the bare contraction of SMA actuators that are incorporated into rings, straps, and wrist bands [8, 26, 62, 67, 77]. One of the early works that amplify the small displacement distance of SMA wires through vertical bars that actuate in different patterns constitutes *The Tickler* [37]. Other work that incorporated SMA wires, demonstrated the use of auxetic structures to invoke squeezing, pressure and twisting gestures [7, 66]. In *KnitDermis* Kim et al. demonstrate how tactile gestures such as compression, pinching, brushing, and twisting can be rendered at challenging convex body locations by embedding SMAs into compliant fabrics using machine knitting [36]. A series of work has focused on the beneficial use of garment compression for therapy and meditation applications; they moreover gathered first findings about the haptic experience of garment compression at different body areas, including the torso, the shoulders and the arms [15, 19–21, 71]. *ShareHaptics* integrated SMAs into gloves and foot ankle braces to provide subtle haptic feedback for mixed reality and VR remote collaboration applications [50]. While clothes provide a very convenient way to provide haptic feedback for everyday applications, the varying properties, such as its thickness, the type of fabric and slack body fit form challenges to properly control the final sensation.

Due to their small form factor, SMA actuators, however, also suit to be integrated into more flexible and compliant interfaces. Recent work has looked into producing more carefully designed stretch and pressure stimuli directly on the skin using the soft actuators. They demonstrate compelling thin on-skin patches that afford to be located at challenging body locations such as the ear, the chest, or the foot ankle [27, 66, 68]. In *Springlets*, Hamdan et al. showed how to fabricate a set of thin and flexible on-skin stickers that are able to mimic natural gestures like pinching, pulling, stretching, and dragging [27]. The authors particularly show how the basic contraction of SMA springs can be utilized in versatile and expressive ways by designing different end-effectors. The demonstrated gestures, however, still depict primitives that mainly make use of one spatial dimension and do not consider more complex spatio-temporal patterns. In contrast, Muthukumarana et al. [46] presented a two-dimensional matrix of contracting SMA wire plasters on the skin within *Touch me Gently*. The authors investigated different temporal actuation patterns and showed how they are able to emulate eight different touch gestures for virtual reality applications. However, they solely focused on the forearm and only utilized the bare compression of isolated plasters in order to generate stretch sensations. Combining both approaches by designing spatially distributed skin-deformation devices and utilizing different end effectors open up various possibilities to explore further expressive on-skin haptic applications with SMA actuators. The authors of *In Contact* suggest to investigate more advanced configurations, such as a network of stretchers and discuss the opportunity of a modular approach as a basis for a future haptic prototyping toolkit [66].

2.2 On-Body Fabrication Toolkits

Through the growing trend of mobile computing, on-body fabrication toolkits have increasingly been proposed during the past years. They offer new ways to integrate sensors and electronics on the body for mobile interfaces and help to fabricate skin conform devices that meet the requirements for wearable on-body applications. In *iSkin* the authors introduce flexible and stretcheable on-skin sensors that can be customized to enable simple to more complex aesthethic touch input devices [73]. In *SkinMarks* Weigel et al. present the fabrication of skin conform I/O devices that support natural touch input gestures and provide passive haptic and active visual cues [74]. Similarly in *DuoSkin* the authors propose a rapid prototyping method for aesthetic skin interfaces with different skin-friendly materials [33]. Nittala et al. present a rapid fabrication technique to create very thin electrode sensor patches using a desktop inkjet printer [52]. Gannon et al. proposed using the skin as input surface for designing and modeling wearable structures [22]. In *ExoSkin* a customized on-body printing device is proposed to print organic 3D structures directly on the skin [23]. While *ExoSkin* makes use of a user operated device to print with non active materials on the skin, Choi et al. present an automated *BodyPrinter* that prints active electronics directly on the skin surface using conductive ink [10]. *ElectroDermis* demonstrates how to embed conventional electronics untethered at challenging locations such as joints through a combination of rigid components and highly flexible connections [42]. The authors provide a tool that allows tailoring a device's shape to specific body location. Through *LASEC* users can rapidly fabricate skin-worn electronic patches with customized stretchability by using different cut patterns [25]. *SkinMorph* demonstrated the fabrication of on-skin biocompatible hydrogel patches that can provide wearable skin output by changing stiffness. Prior work has proposed different fabrication techniques [27, 66, 68] to integrate SMAs on the body including printing 3D printing substrate on clothes [47]. Our toolkit leverages a very similar fabrication process by printing mounting points on skin-adhesive tape that helps to attach ANISMA haptic skin-deformation devices on the skin and can be designed using ANISMA software.

2.3 Prototyping Toolkits Using SMAs

Due to the small form factor of SMAs, several explorative concepts have been proposed that embed the soft actuators into material like foams [12], paper [60], or fabrics [47, 48, 68] to turn them into actively morphing and programmable structures. In some cases, the SMA itself represents the structure [53, 70]. *Surflex* presents one of the earliest concepts of using a mesh of nodes connected by springs to deform foam sheets [12]. *NURBSforms* and *Bosu* propose a new physical programming paradigm to save and restore shapes of objects actuated by SMAs [56, 70]. In *Autogami*, the authors showcase a rapid prototyping toolkit to visually animate paper craft with a **graphical user interface** (**GUI**) [80]. They use selective inductive power transmission to actuate the individual SMAs. A software tool helps the user to design the paper craft, define movement primitives, and assign actuators to them. *Intuino* presents an authoring tool for supporting the prototyping of organic interfaces, including the actuation of SMAs by specifying the waveform manually [72]. The toolkits primarily focus on shape-changing interfaces and do not address the requirements and challenges for prototyping multi SMA devices for the application on the skin to provide haptic feedback.

2.4 Haptic Prototyping and Programming Toolkits

One of the earliest approaches proposing a tool to design haptic patterns and convey information via force feedback is *The Hapticon Editor* [18]. with *HAMLET*, Eid et al. developed a graphical editor that helps assign haptic properties to virtual objects, which can be rendered using force feedback [16]. Shen et al. [51] and Zhu et al. [79] proposed prototyping toolkits to easily create customized passive or mechanical haptic proxies for virtual reality environments. Swindells et al. focused on designing a multi-modal experience and proposed a tool that allows playing vibro-tactile feedback along with audio and visual media content [69]. As vibration depicts the most conventional way to convey information via the skin, most toolkits target controlling arrays of vibration motors and designing their actuation patterns [13, 34, 35, 43, 54, 61, 65]. User-interface elements known from audio and video editing software are often borrowed for this purpose. Our visual programming interface was partially inspired by the scene design by Schneider et al. [64]. While most toolkits allow users to manipulate the raw waveform of the actuators' control signal, a few toolkits have proposed alternative methods, such as using direct manipulation [64] or programming by demonstration [29]. Recently, Pezent et al. published their work on an open-source hardware and software toolkit for low-latency vibratory actuators controlled through audio [57]. Endow et al. [17] introduced a haptic toolkit for compressables based on a pneumatic system. Instead of vibration motors or pneumatic systems, we propose the first end-to-end software and hardware prototyping toolkit for SMA actuators to induce skin deformation stimuli. Our toolkit considers challenges and limitations, such as the comparably high latency and non-linear actuation characteristic specific to SMA actuators.

In a contemporary article about haptic experience design, Schneider et al. call for more haptic toolkits that allow to refine haptic sensations dynamically through quickly programming and testing different configurations virtually [63]. With our toolkit we seek to address both of these suggestions for prototyping with SMA actuators in context of on-skin haptic applications.

3 SYSTEM REQUIREMENTS

We conducted a focus group and semi-structured interviews with 11 HCI researchers to identify their pain points when developing SMA-based actuators and derive requirements for a potential toolkit that helps overcoming these challenges.

Focus Group: We conducted a focus group with 5 HCI researchers between 22 and 30 years ($M = 25.6$, $SD = 3.78$, all male) who are interested in haptic user interfaces to discuss possible on-body haptic applications that can benefit from the unique properties and mechanism of SMAs. The moderator explained briefly what SMAs are and how they work (only one participant had previous knowledge on this topic). Then, he offered participants a chance to directly interact with pre-prepared functional SMA Modules. Following this, participants were encouraged to come up with potential application scenarios and discuss them in the group. Finally, the moderator asked participants to describe the challenges that they foresee when prototyping skin deformation devices with SMAs.

Participants came up with several interesting application ideas. What the applications had in common is that they assumed that a single haptic device would include more than one SMA spring that can be individually programmed to create complex haptic gestures. What they considered to be a challenge was the ability to fine-control individual SMAs in the absence of a closed-loop feedback system. They also pointed out that SMA datasheets, which were provided to participants, were insufficient to make design decisions, such as determining the thickness and length of an SMA spring needed to achieve the desired skin-deformation gesture. Many values such as the different pulling forces are stated as rough guideline in the data-sheets, depending on the application. The participants realized that without further engineering knowledge, they had to trial-and-error in order to make a decision on the right parameters for their application.

Interviews: To infer more information on challenges and needs for effectively prototyping with SMAs, we interviewed 6 additional researchers (2 female, 4 male) working in HCI and haptics and their intersection with soft robotics, virtual, and mixed reality. The researchers stated to have prototyping experience with SMA actuators between one to three years ($M = 2.08$ years, $SD = 0.66$). All had publications on using them to evoke sensations on the skin (two collaborated in one project). They had diverse backgrounds including computer science, biomedical engineering, telecommunication, engineering mathematics, and design. Moreover, one material scientist was interviewed that worked on improving the durability and the shape-changing effect of the alloys. The interview questions were open and included: "In what projects did you work on SMAs?" "How did you approach?" "What did you have to consider when starting prototyping with the actuators?" "What challenges did you face?" "On what did you spend the most time?" "What do you think could have helped you?".

Participants had mixed experiences working with either SMA wires, SMA springs, or both. Most stated that they would prefer working with SMA springs to achieve a more effective deformation force due to the longer displacement length of springs. However, at the same time, they stated that SMA springs seemed more challenging to work with. The springs were more easily being damaged and lost their contraction capability. Overheating, overstretching, cooling time, and challenging power control were the most frequently stated issues. Many reported that it was difficult to deal with high currents without electrical engineering knowledge. The researchers explained that it would be useful to have more continuous control over the power to define the displacement and the exerted force more deliberately. All the participants reported that determining the right parameters for the effective implementation of their SMA configuration was error-prone and very time-consuming. One interviewee stated that he decided to pursue a different problem, as technical obstacles such as power control and the implementation were too troublesome for his original idea. Many stated that they first approached determining a practical design in a trial and error manner. On one side, the participants asked for a tool that could directly determine the optimal parameters. On the other side, many of them wished they had a tool that allows them to explore different configurations and SMA types more quickly in a virtual software environment. They were interested in easily investigating the actuation behavior, pulling effects, and particularly the cool down behavior to estimate the actuators' safe actuation frequency: *Something like an SMA playground would be nice.* (P6), *A toolkit to simulate the movement would be useful.* (P2). Several stated that more complex configurations with interlinked SMAs would be exciting to explore in the future; however, it would increase the design and control complexity: *I think a more deliberate control of multiple SMAs could open up a new dimension of working with SMAs* (P7). Everyone agreed that they would need to test the prototype on the skin ultimately. Above all, to verify the haptic experience.

Key Takeaways: Overall we could observe a desire to develop and explore multi-SMA skin deformation devices that involve more complex configurations and actuate in a programmed way. For the development of these devices, we identified five main challenges. In the following, we elaborate on these challenges and discuss the resulting requirements for a toolkit that aims at helping prototyping with the actuators:

- **Heat Protection:** SMAs quickly heat up and can harm the skin. For a safe operation hence, the actuators need to be encapsulated and isolated from the skin. However, the encapsulation needs to support heat exchange so that the actuator can cool down and actuate again. Furthermore, the device should retain compactness and flexibility as these belong to the most compelling properties of SMA actuators.
- **Robust Attachment:** SMA actuators exert strong linear forces at both ends. If the device does not firmly embed the SMAs, they can loosen and render the device ineffective. The device itself must also be attached to the skin in a reliable way to allow for a robust operation over multiple actuation. To support pulling different end-effectors across the skin, such as a tactor, also other objects need to be attachable to the SMA actuators.
- **Steady and Accurate Control:** The most common method to control an SMA is to start and stop the current flow using a coarse on-off method. However, to generate a pulling force at the desired power level for a specific time, one must control the electrical current that flows through the SMA more precisely. Compared to vibration motors, SMAs draw relatively high amounts of current; working with these currents requires advanced electrical engineering skills. A particular challenge is to predict or monitor the SMAs non-linear actuation characteristic to allow operating SMAs steadily over a longer time. A reliable control model to predict the SMA's behavior or a sensing method that allows for a closed-loop system would provide more precise control of the actuator. Moreover, the actuation frequency is still limited by the cooling time required for the SMA to elongate fully and contract again. A cooling system could increase the actuation frequency and make the actuator accessible for new applications.
- **Operational Limits and Parameter Determination:** SMAs can quickly be damaged through overheating, overstretching, or exceeding the sustainable stress limits. These limits are not immediately visible to the user. They can vary depending on the actuators' type or size and hence need to be determined individually. Configurations comprising multiple interlinked actuators further increase complexity, as one needs to keep track of every parameter and constraint. For example, when two SMA actuators are supposed to pull at each other,

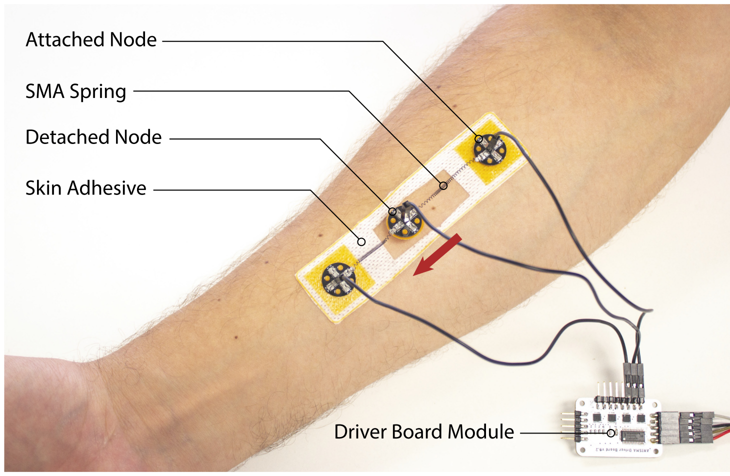


Fig. 2. A skin deformation slider designed using the ANISMA toolkit. The slider comprises two SMA springs and three nodes: Two Attached Nodes that anchor the SMA springs to the skin at the sides, and one Detached Node that drags an object over the skin in the center; the Detached Node is pulled to one side using the contraction of an SMA spring.

the designer has to ensure that contracting one actuator does not overstretch the other. A system that makes the user aware of the operational limits and eases determining important parameters can help finding a practical design more quickly and prevent damaging the costly actuators during their operation. We identified eight actuator parameters that are important to consider: the actuator's *size* and *type* which define the actuators actuation characteristic including its heating behavior; the *minimal stretch length*, *maximal stretch length*, and *maximal sustainable stress* to stay within mechanical limits; the *actuation frequency*, *exerted force*, and the SMA's *displacement* as important output parameters to generate skin deformations.

— **Implementation Effort:** One essential step of developing a skin-deformation device is verifying its behavior and the haptic experience. However, slight modifications often require rebuilding the whole prototype, as the SMAs need to be crimped and firmly embedded into the device. The expensive actuators often are not reusable, and the old prototype needs to be discarded. Hence building a customized prototype repeatedly is costly and very time-consuming. It furthermore requires various fabrication skills. A system that eases the physical implementation and offers a simple way of iterating on a design could allow the designer to focus on the essential task, i.e., designing and testing sensations on the skin or exploring new SMA configurations.

4 ANISMA

ANISMA is a toolkit for designing and fabricating wearable skin-deformation haptic devices embedded with SMA actuators. The toolkit comprises the open-source[1] ANISMA software, a design and animation tool; and ANISMA hardware, a kit for building and controlling skin deformation haptic devices.

Every skin deformation device is composed of at least one SMA Module. An SMA Module consists of a single SMA spring that connects two Nodes. The Nodes can either be attached to the skin

[1]ANISMA GitHub Repository https://github.com/augmented-human-lab/ANISMA.

(skin Attached Node) or to objects (skin Detached Node). This way, the SMA spring can directly pull and deform the skin or alternatively drag objects along the skin.

In this section, we present the end-to-end process of creating and actuating an ANISMA skin deformation slider device (Figure 2, which serves as a good example to demonstrate the different functionalities of ANISMA.). This covers most toolkit elements including design, animation, fabrication, and programming.

The slider device is composed of two SMA springs (SMA Modules) that are attached to the skin from one end via an Attached Node, and interlinked from the other end via a single Detached Node hovering over the skin. The device is connected to ANISMA control unit that is programmed with an actuation sequence. At actuation, one of the SMA springs is controlled to contract at a certain speed to drag the Detached Node over the skin in the corresponding direction.

4.1 Design and Animation

4.1.1 Defining the Device Layout. The user begins the design process using the ANISMA software environment. In the center of the design view (Figure 3, top), the user is provided with a workspace where she can place and manipulate SMA Modules. The legend at the bottom left corner helps novice users identify the different workspace elements (Figure 3(b)). All device layouts that the user specifies within the indicated 3D printing area can later be translated into a physical prototype in one go (see Section 4.2).

To drag an object back and forth a user may want to use two springs that pull a shared Node through contracting the springs individually. To design the targeted deformation device with two connected springs, the user selects the module tool (first item in Figure 3(a)). Using this tool, the user can now freely place and arrange two SMA Modules. Connecting individual SMA modules is achieved by overlapping two Nodes, which automatically snap together.

Newly generated SMA modules inherit standard specifications regarding SMA type and initial build setup. The user can change these specifications in the tool settings panel (Figures 3(d) and 3(e)). Based on our experiments with SMAs, we decided to provide templates for four different SMA springs, varying in thickness and length. The user is additionally able to choose an initial contraction length percentage for the chosen SMA. An initial contraction length of 50% normally yields the largest effective movement area for a Node connected to two SMAs (green color area in Figure 3(c)). Our software additionally supports if a user chooses to build her own SMA Modules outside of our provided templates. The custom module tool (second item in Figure 3(a)) supports the free placement of two Nodes and generates the SMA accordingly, providing the user with information on how to build the module.

Relocating an already placed Node, by dragging it to a new position, stretches or compresses the SMAs connected to it. The effective movement area of Detached Nodes is updated accordingly in real-time, allowing the user to observe the effects of changing node layout and SMA states. A percentage value shown above every SMA indicates the SMA's actual contraction length (Figure 3(c)). We allow users to exceed the stretch and contraction limits of the SMAs while dragging nodes, as our pilot tests showed that users want total control over layouting before fixing overstretch (<0% contraction) or over-contraction (>100% contraction). Our software marks these problems in red.

By default, all nodes from new SMA Modules are marked as attached to the skin. These element specific parameters can be altered by opening the element's context menu. In our example, the user would right-click on the center node and select "Detach Skin" to declare it as a Detached Node. This enables animation and simulation of the real behavior later prior to fabrication (see Section 4.1.2, 4.2). Similarly, the outer Attached Nodes have to be further stabilized so that the contraction force of the SMAs is mostly used to drag the center Detached Node and not pull the skin. The user can achieve this by selecting our area brush tool (third item in Figure 3(a)) and drawing rigid

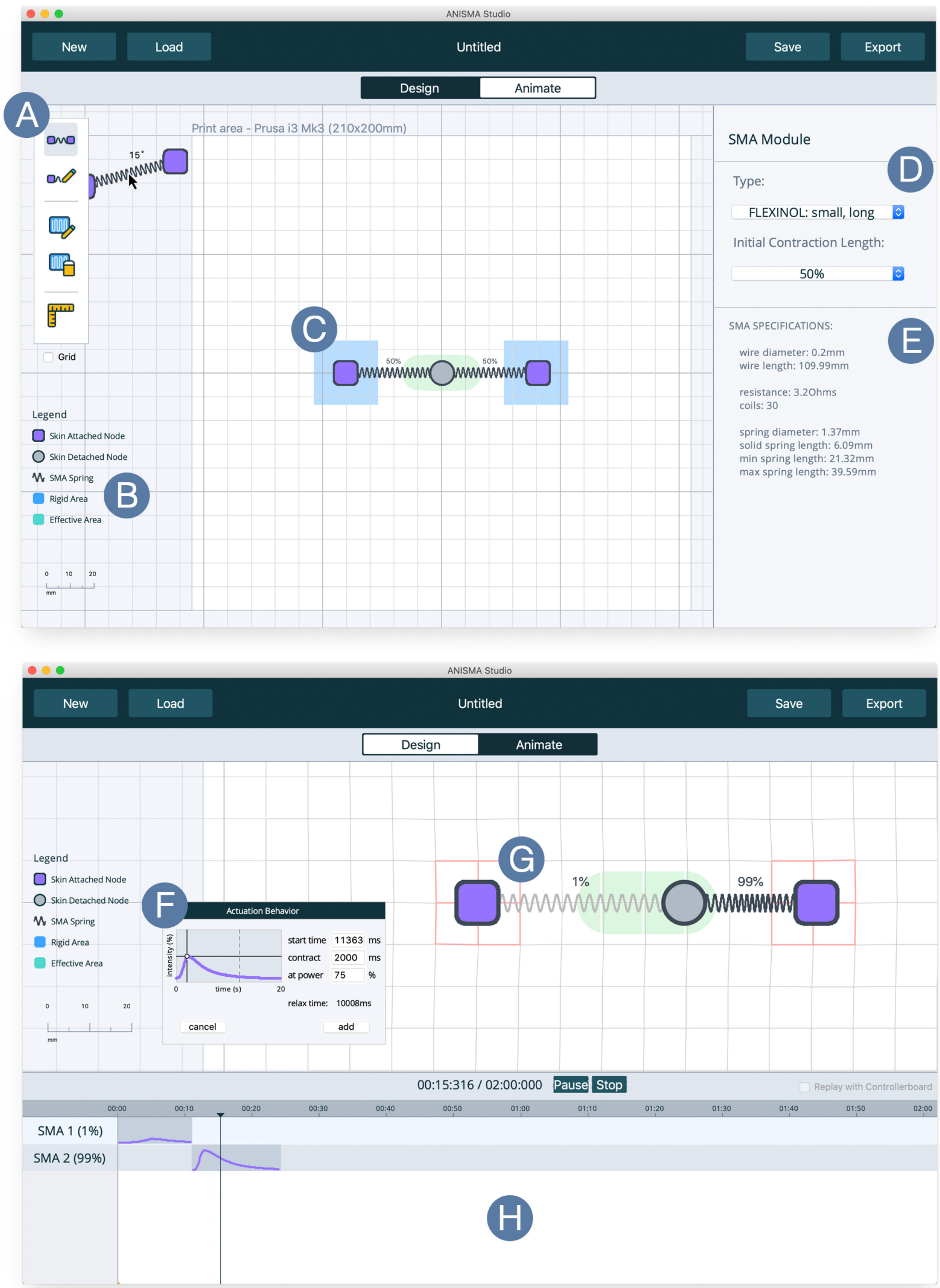


Fig. 3. The two main views of the ANISMA Software: The user can specify a layout in the design view (top), and program and preview the device's actuation behavior in the animation view (bottom). Interface elements: toolbar (a), legend (b), actuator layout (c), tool settings (d), selected SMA specifications (e), actuation parameters (f), device actuation preview (g), timeline view (h).

areas around the outer Nodes (blue markings in Figure 3(c)). For a single SMA Module with two skin Attached Nodes, the user may furthermore use this feature to create a non-uniform skin deformation by supporting one Node with a larger rigid area compared to the other. On actuation, the pulling force at the unsupported Node can this way result in a larger movement toward the supported Node. The user can alter the thickness and size of the rigid area to change the effect. Similar to conventional painting software, we also provide an area eraser and a ruler to measure the resulting areas and module layout to determine if a design fits to the desired real-world application (fourth and fifth item in Figure 3(a)).

4.1.2 Designing and Previewing Actuation Sequences. When satisfied with the first draft of a layout, the user can switch to the animation view (Figure 3 bottom) to define and preview the deformation device's actuation behavior. The animation view offers the user a visual programming interface that does not require any coding skills. A user can specify an actuation sequence in the timeline view (Figure 3(h)) and preview the device's behavior in the workspace above (Figure 3(g)).

For every SMA Module, the software displays a track in the timeline view that shows its corresponding sequence of actuations. The individual actuations are specified for each SMA Module in the same way, independent of connected Attached Nodes or Detached Nodes. In our example, the user wants to slowly drag the slider's Detached Node to the left and then quickly to the right. To achieve this, she needs to define the actuation of the left SMA Module first, followed by an actuation of the right SMA Module. The user selects the left SMA Module in the workspace, which opens a pop-up window where she can specify the actuation parameters (Figure 3(f)) like start time and the current (power) provided over a specified contraction time. The system plots the resulting characteristic nonlinear actuation curve, indicating to the user how the force intensity develops over time. This aids in estimating how fast the SMA produces tension when heating up and how long it will take to cool the SMA down. The actual information portrayed by the curve depends on the context. For a simple pinching device with one spring and two skin attached Nodes, the user may derive an approximation of how the pressure exerted on the skin develops over time. In our example, the force intensity shows how much an SMA pulls at the Detached Node.

Additional to the indirect manipulation of the curve by setting its parameters by typing their values, our software allows direct manipulation of the curve. The user can drag the local maxima to the desired position, simultaneously changing the force and time (Figure 3(f)). To achieve the wanted slow movement to the left, she drags the maxima further to the bottom right, which equates a weak force over a longer time period. To prevent damage to the SMA being actuated, our software restricts the input space for both manipulation methods automatically. For example, it is only possible to turn on a small SMA at maximum power for about 1.6 *seconds* but excite it up to 10 *seconds* at a lower power level (see Section 4.1.3). Pressing "add" adds the actuation to the timeline (Figure 3(h)). The user can also create an actuation directly from this timeline to skip setting the start time manually.

An actuation, added to the timeline, appears as a clip in the SMA's respective track (Figure 3(h)). The software indicates what track belongs to which SMA by highlighting both if the cursor hovers over either of them. The user can rearrange the clips as in conventional video-editing software and, in this manner, design a temporal actuation pattern. The software does not allow overlapping clips on the same track and only permits actuating an SMA again if it is thoroughly cooled down.

To preview the designed actuation behavior, the user presses the play button and our software shows a real-time simulation approximating the actual actuation behavior based on our empirically derived actuation model (see Section 4.1.3). The forces of skin Attached Nodes are previewed by deforming a 2-dimensional mesh that roughly simulates the behavior of an elastic matter such as the skin. Rigid areas are indicated in red and cause the mesh to be less easily deformed by forces

(Figure 3(g)). Users can use the preview to get an idea of the effect of the SMAs pulling forces in different ways: for a single SMA Module with two Attached Nodes, the user can observe how an SMA spring may deform the skin. In our example with the Slider, the user can monitor the simulated movement of the Detached Node hovering above the skin. Most importantly, it can help a user verify whether the device is working as intended and, e.g., detect if an SMA overstretches during the actuation sequence. By switching between the design and animation view, a user can virtually explore how a design change affects the device behavior without spending time on fabricating the physical prototype.

4.1.3 Actuation Model. Based on our experiments with different SMAs, we selected two sizes of SMAs (1.37 mm and 2.54 mm spring diameter) to offer users the choice between a thin, quickly actuating SMA as well as a bigger, stronger, but also slower actuating version. To derive the actuation characteristics about the exerted force overtime for both sizes, we recorded five measuring series each (five different current levels $0.3A - 0.7A$ small, $0.8A - 1.4A$ big). Prior to each measurement, the spring was elongated and a baseline actuation was performed at $0.6A$ and $1.0A$, respectively, to achieve the same initial condition. The measurements were performed at 22.0 degrees Celsius. Tests for both SMAs were using 30 coils, from the maximum recommended elongation distance as shown in Figure 4 (left). We measured the pulling force using a FUTEK 250g Load Cell and a NI DAQ USB-6218 interface. We used our physical Nodes to firmly connect the SMAs to the load cell and a solid mount. The mounting and interlocking system did not break anytime during our experiments comprising more than 40 test measurements using different sizes of SMAs.

Based on the measurement series, we were able to derive a basic actuation model that allows predicting the individual actuation characteristics for the heat-up and cooling phase for an SMA at a specified current value. Using least-squares regression, we first fit a Sigmoid function to the individual heat-up and cooling phases. We then determined two quadratic functions that describe the scaling behavior at the different power levels. Finally, we obtained a function describing the force $F(\Delta t_{act}; p)$ for the actuation time t_{act} of an SMA actuator that is powered with current p. This way, we determined a function for the small and big SMA types individually. Figure 4 (right) shows three measurement series and the predicted intermediate actuation curves for the heat-up phase of the small SMA spring. As our parameter estimation is based on quadratic formula, our force prediction function does not extrapolate well for higher power levels ($> 0.7A$ small SMA, $>1.4A$ big SMA). For the implementation of the actuation model, we defined two timely restrictions to support a safe operation based on our model: (1) Based on repetitive actuation tests, we decided to restrict the actuation time by the time it takes an SMA to reach a defined maximum force of $123.63g$ for the small SMA, and $320.95g$ for the big SMA. Power level is determined individually for an SMA according to our actuation model. This results in a maximum actuation time of 1.6 *seconds* for the small SMA and 4 *seconds* for the big SMA at the highest power level ($0.7A$ small SMA, $1.4A$ big SMA, respectively) (2) As we cannot guarantee an accurate and reliable prediction for arbitrary long actuation times at lower power levels, we, furthermore, set an overall actuation limit of 10 *seconds*.

4.1.4 Simulation. To simulate the SMAs actuation behavior and the skin deformation effects in our software environment, we implemented a mass-spring system.

Before replaying an actuation sequence in the *animation view* (see Figure 3, bottom), we generate a 2-dimensional mesh around the skin Attached Nodes, which simulates the skin. We use a rectangular mesh with diagonal sheer springs. To give the mesh a more natural property, we introduce additional anchor springs to simulate the underlying soft tissue similar to [75]. The anchor springs drag the Nodes of the skin mesh toward their original location. This imitates the skin

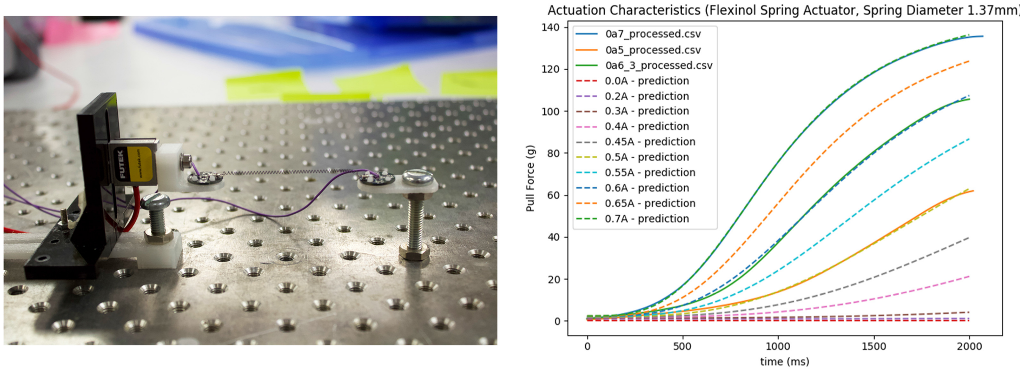


Fig. 4. Measurement setup (left) and measuring series for deriving actuation characteristics (right).

relaxing behavior that can also provide a bias force to the actuator and pull an SMA back to its original elongated state after a contraction.

Every spring connects two Nodes i and j. The force of skin and anchor springs is calculated in the same way $F_{skin} = F_{anchor} = -kx - d(v_j - v_i)$, where k is the spring constant and x is the relative displacement from the springs resting length [41]. d depicts the damping factor multiplied by the relative velocities of the spring Nodes i and j. For SMA springs, we substitute the spring constant by the time-dependent actuation force divided by the maximum elongated length l_{max} of the spring. Hence, we obtain $F_{SMA} = -\frac{F(\Delta t_{act};p)}{l_{max}}x - d(v_j - v_i)$. We then calculate the system state for each discrete time-step by the following scheme using Verlet integration:

ALGORITHM 1: Simulation Step i+1

for each $n \in nodes$ **do**
  calculate netforce $F = \sum F_{skin} + \sum F_{anchor} + \sum F_{SMA}$ at node n
  obtain acceleration $a = F/m$ for node n with mass m
  update the position $p_{i+1} = 2p_i - p_{i-1} + a\Delta t^2$ for node n
end for

The spring constants for our mesh are calculated as proposed by [41]. While our approach began by approximating the mechanical skin properties using Young's modulus and Poisson's ratio, we largely adjusted and fine-tuned the parameters manually through trial and error in the end. Hence, our simulation is only suited to predict the skin's behavior roughly. Moreover, it does not consider varying properties of body areas with looser or tighter skin that effect the device's behavior.

4.2 Fabrication and Assembly

We propose a reliable and straightforward method to translate the virtual layout into a physical prototype and test it on the skin. This way, a user can even reload an old design at any time and easily replicate it using our toolkit.

On pressing the export button, the software generates an "STL" file that contains information about the node mounts and rigid areas, as specified in the virtual design. Using a CAM application, the user can convert the file into a print job that is executable by a 3D printer. To print the design onto skin adhesive, the user places the skin tape with double-sided tape on the printing bed and adjusts the Z-Level to +0.23 mm above the standard printing height. For our experiments, we used an Original Prusa i3 MK3S with PLA filament and the PrusaSlicer software (2.2.0) set to 0.1 mm

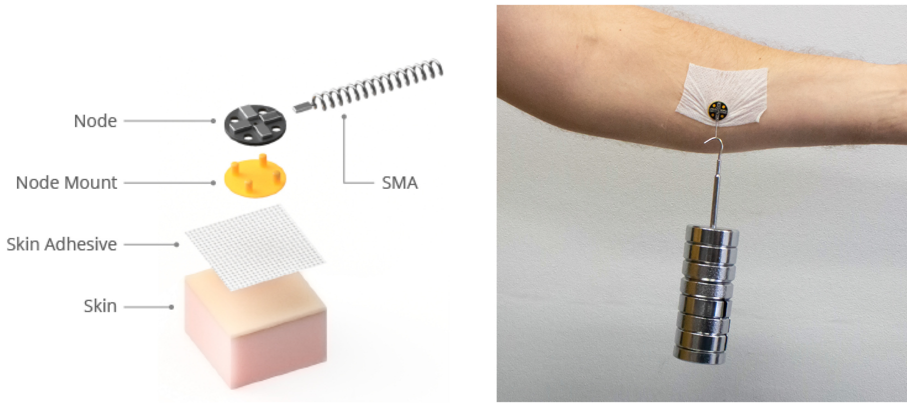


Fig. 5. Skin Attachment Concept (left): For any virtual Node, a *Node Mount* is generated and printed on *Skin Adhesive* which allows pasting the design on the skin. The physical *Nodes* can be plugged into the *Node Mounts* and up to four SMAs can firmly be anchored to the designated slots on a single *Node*. We tested our skin attachment robustness by attaching a test weight of $800g$ at one of the slots (right).

layer thickness. After the print job is completed, the user can assemble the device in four steps: (1) The user applies heat insulation tape along the SMA connection paths. (2) The user attaches the Nodes to the designated node mounts. (3) The user can then plug the SMAs into the corresponding SMA slots. (4) Finally, the user connects the Nodes to the Driver Board using wires. The ANISMA software informs the user about what Node needs to be connected to which pin of the Driver Board. After the assembly process, the user can paste the device directly on the skin, program it using the software, and replay different actuation sequences.

Figure 5 illustrates the skin attachment technique, we use to ensure a robust anchoring of the SMAs to the skin and interlink the actuators with each other firmly. A node provides four holes that can be connected to a node mount. The node mount incorporates four corresponding pins with a thickened tip which allows snapping both parts together. In the same way, detached nodes can be attached to objects. For example, we designed a cone-shaped tactor, which is 3D printed and provides four pins similar to node mounts fixed on the skin. Detached nodes could moreover be attached to objects using M2 screws or fiddling threads through the nodes holes. A node additionally offers four SMA slots with a snapping mechanism that allows connecting SMAs and prevents them from falling off. The software warns the user if any design issue, such as overstretching, have been detected before exporting or actuating the physical prototype. Furthermore, the user is encouraged to simulate at least once to identify problems that may only become apparent while actuating the SMAs. This mechanism hinders the user from accidentally fabricating ineffective designs and, this way, can save valuable time or even prevent damaging the actuators. We found that PLA print filament can be printed quicker than flexible filament and remains flexible enough to align to body curvature but provides a stiff base for shear forces.

4.3 Control

Our control unit comprises an Arduino Uno as *Controller Board* and our customized *Driver Board Modules*. The *Driver Board Modules* (see Figure 6, left) support eight output pins that are fully controlled and can be extended by adding more *Driver Board Modules* to an I^2C bus system. We use a PCA9685 16-channel LED controller in combination with four MAX14874 dual-channel push-pull drivers in order to control the current flow using **pulse-width-modulation** (**PWM**) and dynamically set the polarity (VCC, GND, HIGH-Z) for each output pin. Our control method allows

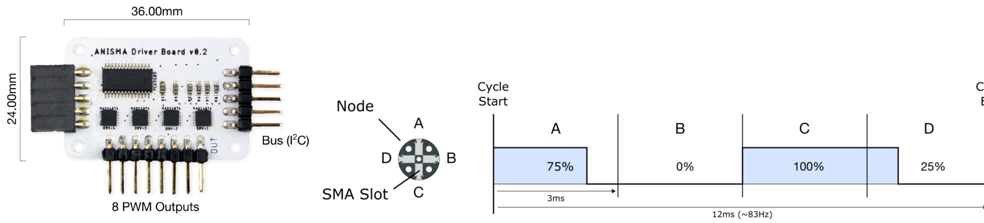


Fig. 6. **Control Unit:** A *Node* can be connected to one of the 8 fully controllable PWM output pins of a *Driver Board Module* (left). Multiple *Driver Boards* can be connected to a shared I^2C bus system. Multiplexing allows to individually control up to four SMAs (A, B, C, D) connected to a single *Node*. An exemplary *control cycle* shows the actuation of three SMAs (A, C and D) at different power levels (75%, 100% and 25%; right). Each SMA is updated at a frequency of $\sim 83.33Hz$ and takes one quarter of the full *control cycle*.

to reduce the amount of required connector cables and thus simplifies the wiring and the assembly process for the user. Instead of up to four connector wires required per *Node* as in *Surflex* [12], we only need one.

We achieve the individual control of four SMAs by using multiplexing. The Arduino runs a stable power control cycle at $\sim 83.33Hz$ to update the pins according to instructions from a connected computer. For each *control cycle*, the Arduino updates the power level of all pins. One *control cycle* is divided into four phases (see Figure 6), representing the SMAs of a single *Node* in clockwise order. As the PCA9685 allows to update all PWM pins (also across multiple boards connected to the shared bus) in parallel, we can synchronize these phases at multiple *Nodes* and this way update the power of all Nodes within 3ms intervals. The MAX14874 motor drivers support 2.5A peak motor currents which is sufficient to drive four small SMAs at the same time. Our tests showed that we also can control bigger SMAs this way, however, with the multiplexing technique the average current that is drawn is lower and hence they take longer time to contract. To obtain a similar contraction behavior as before we decided to reduce the number of big SMAs to two per *Node* and in this case divide our control cycle into two phases.

The Arduino *Controller Board* can be instructed via a serial interface. Each instruction contains information about at least one pin, the corresponding power level, and its actuation duration. The Arduino then updates the *Driver Boards* accordingly within the *control cycles* and autonomously turns-off the pins after the actuation time is expired. Our implementation ensures, that the update time of any pin can maximally deviate by $12ms$.

4.4 Advanced Prototyping

One strength of ANISMA is the versatility in regard to generating designs of different complexity. The aforementioned slider is one of the basic building blocks, already established in prior work. We present three additional prototypes based on this basic building block to show how ANISMA enables fast iteration of more complex designs and the resulting wide range of achievable sensations on the skin.

The Twister (see Figure 7, left), shows how multiple sliders like building blocks can be combined to generate complex haptic sensations, leveraging the control ANISMA provides. Like a standard slider, the outer nodes of the two *Twister* parts are bound to a rigid area. In contrast to a standard slider design, the moving inner nodes are attached to the skin. These small design changes combined with the simple parallel layout of these two parts enables the rendering of more complex gestures like a clockwise or counter-clockwise twist, and push the skin from one side to the other. The fast iteration of node design and layout of blocks combined with the continuous control

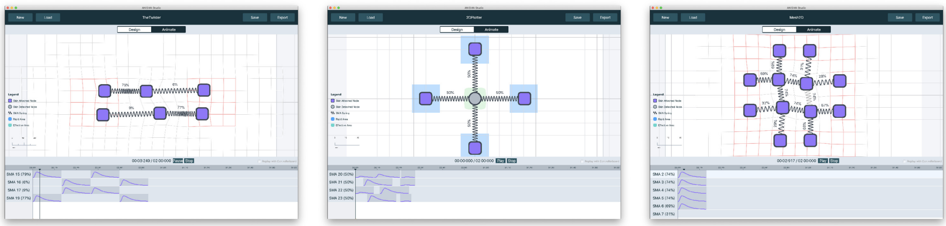


Fig. 7. Advanced prototyping examples showing varying grades of complexity achievable with ANISMA. Left: The Twister. Middle: The 2D Plotter. Right: The 2D Mesh.

enabled by our control system shows great potential in generating a wide range of sensations with a limited number of mostly unchanged basic building blocks.

The 2D Plotter (see Figure 7, middle), shows how the ability of 1-dimensional plotting, achieved by the slider can be extended to 2-dimensional plotting on the skin. It essentially uses two merged sliders in a perpendicular layout sharing one tactor. The tactor is dragged across the skin to render diverse gestures. These gestures might include shapes representing abstract concepts, but also icons or smilies conveying rich information. This concept is similar to known *Skin Drag Displays* [31], but comparably thin and devoid of disturbing vibrations thanks to the SMAs' properties.

The 2D Mesh (see Figure 7, right), shows our system's scalability moving away from basic building blocks to topologically complex structures, allowing to render multiple gestures simultaneously. It comprises 12 SMAs in a rectangular mesh layout. Every node is attached to the skin. Leveraging the time multiplexing built into our control system, the *2D Mesh* enables the generation of various two-dimensional skin stretching gestures on different skin areas at the same time. While extending the mesh increases the number of nodes by the power of two, our control unit reduces the number of required wires in this configuration from four to one per node. This significantly reduces the wiring complexity and simplifies the fabrication of similar devices. However, as a drawback interlinking, the SMAs in this manner generates a resistor network, which may lead to actuating connections that were not intended to be actuated.

4.5 Running ANISMA Software

The ANISMA software[2] is written in Python and runs locally on a computer using Python version 3.9 and several external libraries with permissive free software licenses (as listed below). The GUI leverages the standard python Tk GUI toolkit package (tkinter) for drawing canvas with largely customized UI elements. ANISMA is cross platform compatible and has been tested under macOS Big Sur Version 11.4, Windows 10 Home N 10.0.18363, and Ubuntu 20.04 using python3.9.

To run ANISMA software, the following dependencies are required which can be installed with the common python package installer "pip":

- **shapely 1.7.1** (3-Clause BSD License, used for 2D geometric object generation and manipulations) [24]
- **trimesh 3.9.21** (MIT License, used for 3D triangular mesh generation and .stl export)
- **triangle 20200424** (LGPLv3 License, used for 3D triangular mesh generation and .stl export)
- **numpy 1.21.0** (3-Clause BSD License, used for array and mathematical calculations)
- **pyserial 3.5** (3-Clause BSD License, used for serial communication)
- **image 1.5.33** (3-Clause BSD License, used for loading, and resizing icons)

[2] ANISMA-software GitHub Repository https://github.com/augmented-human-lab/ANISMA-software.

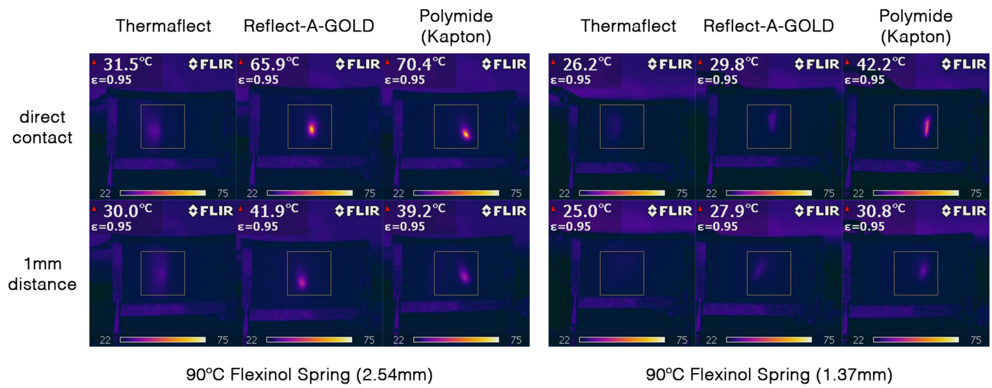


Fig. 8. Comparison of three thermal heat insulation tapes for thin and thick SMAs at maximal actuation using ANISMA toolkit.

To start the ANISMA software the user uses a terminal or command prompt to locate to the ANISMA software root folder and executes the "main.py" python script using python3.9.

5 HEAT PROTECTION AND ENCAPSULATION

In this section, we discuss possible ways to shield the heat of SMA actuators from the skin based on our own experiments that allowed us to safely prototype with ANISMA skin-deformation devices. While ANISMA does not consider a full encapsulation of the actuators, similar methods as reported by prior work can be used to further embed the actuator in an enclosure [27].

ANISMA uses 90-degree Flexinol Spring Actuators that completely restore their preprogrammed contracted shape around 90 degrees and can heat up to 120 degrees under recommended operation. We monitored the surface temperature of the bare actuators using a FLIR i50 Infrared Camera for 14 contractions at maximum actuation power and frequency using the ANISMA toolkit. After the first two contractions, the temperature did not show any heat accumulation over time for both types of thickness. The actuation temperatures for the big SMA (2.54 mm) alternated below a peak maximum of 114 degrees Celsius and a peak maximum of 91 degrees Celsius for the small SMA (1.37 mm). In many cases, a small gap between the skin (plaster) and actuator can already shield most of the heat. However, as bending of skin and actuator can occur, this cannot always be ensured. We, therefore, investigated the shielding capability of three different heat insulation tapes (Thermaflect[3], Reflect-A-GOLD[4] and a commonly available polyimide (Kapton) tape[5]) at maximum actuation power and frequency in two conditions: 1) direct contact (worst-case) and 2) a 1 mm gap to the plaster (see Figure 8). We found that while all three tapes state to easily shield heat for over 120 degree Celsius, they do not all completely isolate heat at direct contact. While one layer of very thin and flexible Polymide tape (0.055 mm) allows insulating the heat from the skin in most cases, it does not completely shield the heat and requires multiple layers for the thicker SMAs. Most effectively we could shield the heat with Thermaflect tape. It reliably isolated the heat even in case of full contact with the skin adhesive (see Figure 8). A drawback of Thermaflect tape is that it is thicker (0.81 mm) and less flexible. A combination of both tapes can be used to obtain

[3]https://cardwells.co.nz/heatshield-products-therma-foil-tape.html.
[4]https://cardwells.co.nz/dei-heat-reflective-tape.html.
[5]www.jaycar.co.nz/polyimide-hi-temp-tape-16mm-x-33m/p/NM2892.

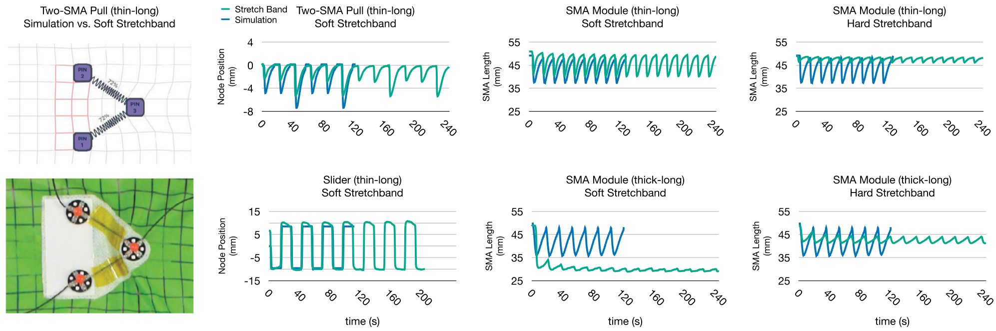


Fig. 9. Technical evaluation of consistency of actuation.

flexibility and a very high shielding effect, as the Thermaflect tape can be used as a buffer to retain distance between the actuator and the Polymide tape.

6 EXPERIMENT 1: ACTUATION CONSISTENCY AND SIMULATION

We tested our actuation model and simulation for consistency over multiple actuations under more predictable conditions using two types of stretch bands: A light stretch band that gets close to the skin flexibility on the back of the hand and forearm (GAIAM Performance Flatband light resistance $1 - 3kg$), and a heavy stretch band that approximates the properties of less flexible skin such as the upper arm (GAIAM Performance Flatband heavy resistance $5 - 7kg$). The stretch bands were mounted on a stable grid plate via M6 screws with an underlying sponge to simulate underlying soft tissue and prevent the bands from easily bending downward.

We investigated essential ANISMA skin-deforming devices consisting of SMA Modules with short and thick SMA types, a Slider with a Detached Node, and a V-shaped configuration of two SMA Modules pulling at one Node in parallel (see Figure 9, left). To track the Node positions we attached red markers to the center of the Nodes and recorded the actuations from the top using a Canon EOS Rebel T3i camera. We used Physlets Tracker 5.1.5[6] to visually trace the Node positions and calculate the SMA length change over time. We contracted each SMA configuration for four minutes at maximum power and frequency. For the Slider, we alternated between actuating the two SMAs pulling at the center Detached Node. For the V-shaped configuration, we first actuated the top SMA, then the bottom SMA, and then both at the same time.

Actuation Consistency and Elastic Deformation Behavior: We plotted the change in SMA length overtime for the single SMA Modules, the relative horizontal position change of the center Detached Node, and the relative horizontal position change of the single Node pulled by two SMAs in Figure 9 (green). As the plotted graphs in Figure 9 (green) show, our actuation model could provide consistent contractions for repeated SMA actuations at maximum power and frequency over four minutes for different SMA configurations. Only when deforming the soft stretch band using thick SMAs, we could observe a major change of the deformation behavior at the beginning. As the soft stretch band did not provide enough bias force to elongate the thick SMAs during the relaxation time, the thick SMA contracted for a long-distance only once at the beginning. Afterward, it was only elongated partially and squeezed the stretch band further until it evened out at a small contraction distance of 1–2 mm. In contrast, the small SMA was easily elongated by the hard stretch band. However, it could only stretch a fraction of the hard stretch band compared to the soft one.

[6]https://physlets.org/tracker/.

The examples of thick SMA vs. soft stretch band and thin SMA vs. hard stretch band highlight the impact of differences in skin elasticity that can influence the operation of SMAs and need to be tested individually. While thick SMAs are stronger, they also require a higher bias force to elongate them again. However, as the example with two SMAs pulling at one Node demonstrate one can achieve a similar displacement using two small SMAs. Depending on the application one may therefore decide to choose two small SMAs over one big SMA to afford an easier relaxation at soft skin and a higher actuation frequency.

Simulation Accuracy: While the simulation approximated the soft stretch band deformation behavior with thin SMAs well for different configurations, it did not provide a realistic estimate for altering elasticities and big SMAs, which showed to require higher bias forces. Our simulation, yet did not consider different skin elasticities and the individual minimum force required to elongate an SMA again. As the graphs from Figure 9 indicate, it still suits to preview effects such as different force amplitudes of varying SMA types, or to get an idea about direction and amplitude changes based on the net forces resulting from multiple SMAs pulling at a single skin Attached or Detached Node.

During our experiments, we further investigated changing the power level of the pulling SMAs of the Slider design. While the simulation could preview the resulting motion and speed changes for full contractions reasonably well (see Figure 9), it did not accurately model the friction and mechanical spring resistance. So far, the software appeared not to be suited to accurately acquire a specific Node position based on the simulation of a single SMA pulling at a Detached Node. This was particularly the case for the big SMAs which provide a higher mechanical spring resistance as discussed before.

7 EXPERIMENT 2: PERCEPTIBILITY

To (1) verify if ANISMA essential skin deformation devices can be perceived on the skin and (2) investigate whether parameter variations can affect their perception, we conducted an initial preliminary user study. We particularly wanted to investigate the haptic sensation produced by three basic skin deformation devices consisting of a *Pincher*, a *Stretcher,* and a *Stroker.*

The *Pincher* comprised a single SMA module with two skin Attached Nodes connected through an SMA spring. When actuated, the SMA contracts and squeezes the skin between the two Nodes. The *Stretcher* was identical to the *Pincher* but supported one Node with a 4×4 cm rigid area (0.2 mm thickness) which introduced planar rigidity but still bent with the skin curvature. As one end was more rigid, the flexible side was more likely to be stretched toward the Node with a rigid area when actuated and could provide a dominant directional stretching cue. The *Stroker* was built using the slider design described in the previous sections with two skin Attached Nodes connected to a detached node in the center. A 3D printed cone-shaped tactor with the tip facing the skin was attached to the center node to stroke the wearer. While the *Pincher* and *Stroker* resembled similar devices to the *Pincher* and *Dragger* in Springlets [27], we sought to investigate a *Stretcher* instead of the Presser, as it makes use of a feature specific to the ANISMA toolkit which we wanted to investigate.

We wanted to investigate the devices on the forearm, as a common body location for haptic feedback. Within pilot tests with four participants, we identified that thin and short SMAs are mainly suited to induce light squeezes. Big-long SMAs could better generate dominant stretching cues at the arm through stronger forces and larger displacement. For the *Stroker*, we found that thin SMAs would be strong enough to drag the tactor, but the direction was hard to perceive when the tactor was dragged over a small distance using short SMAs. We hence decided to use big-long SMAs for the *Pincher* and *Stretcher*, and thin-long SMAs for the stroking device. The three devices were designed to encompass the same plaster footprint size of $5 \times 10cm$. To achieve a slow pinching and stretching gesture the *Pincher* and *Stretcher* were actuated at 75% power for

6 *seconds*; to achieve a fast gesture both devices were actuated at 100% for 2.5 *seconds*. The *Stroker* was actuated at 100% for 1.6 *seconds* to obtain a fast stroke, and at 50% for 6 *seconds* to obtain a slow stroke. We used a typical soldering helping hand to fixate the wires and prevent them from touching the skin. This also helped to keep the tactor straight, as it could sometimes be pulled to the side through the attached wires. We isolated the heat for the *Pincher* and *Stretcher* using a combination of Polymide and Thermaflect tape as discussed in Section 5.

We conducted a within-subjects design with independent variables being DEVICE {Pincher, Stretcher, Stroker}, SPEED {slow, fast}, and ORIENTATION {facing toward, facing away}. The *Pincher* depicted a particular case (i.e., no directionality) as it was symmetric.

7.1 Participants

Eight new volunteers, two females, six males, ages 23–32 years ($M = 28.49, SD = 3.2$), participated in the study. Three participants had prior experience with non-vibrotactile haptic feedback, all but one right-handed.

7.2 Method and Procedure

The preliminary study took place in a controlled environment at 22 degrees Celsius. The participants were blindfolded using a sleeping mask and sat in front of a desk, the dominant arm resting comfortably on a table with the hand palm facing up. The participants were asked to retain their posture as much as possible during the whole experiment. They were told that they could take a rest anytime they needed; and always asked if they wanted to rest after twelve subsequent trials. DEVICE, SPEED, and ORIENTATION were counterbalanced. For each trial, the participant experienced a new DEVICE placed on their inner forearm similar to [66]. The device was always mounted with a specific ORIENTATION. The Stroker was actuated before placing it on the skin to move the tactor to one side. After placing it, the other SMA could then drag the tactor to the opposite side. After mounting the device, the experimenter signaled the participant that the new trial starts, and the device was actuated at a specific SPEED after a random delay within ten seconds. If the participant did not perceive any stimuli, the instructor pretended to move on with the next trial but repeated the prior trial once without the knowledge of the participant, which involved unmounting and remounting the device on the skin. The participants were told to press a buzzer as soon as they felt any stimuli to measure their reaction time. After this, they were asked to describe the sensation in their own words before classifying it either as Pinching, Stretching, or Stroking. The participants were then asked questions about the sensation: Did you perceive a direction toward your body, away from your body, or no direction at all? Did the speed of the sensation feel fast or slow? How noticeable was the sensation? (1 not noticeable at all, 5 very noticeable) How comfortable did the sensation feel? (1 not comfortable, 5 very comfortable). For the classification, direction and speed, the participants were further asked to rate their confidence of the provided answer on a 5-point Likert scale (1 No confident at all, 5 very confident).

Overall, the experiment comprised 3 DEVICE × 2 SPEED × 2 ORIENTATION × 3 repetitions × 8 participants = 288 trials. One user session took about 1 hour (M = 62.15 minutes, SD = 6.6).

7.3 Results and Discussion

Noticeability: Overall the three basic ANISMA skin-deformation devices were noticed easily by participants. Noticeability was rated high on average with $M = 4.18, SD = 0.78$. Only in two instances the Stroker did lose contact with the skin and was not perceived at all. Faster actuations appeared to be rated slightly more noticeable than slower (see Figure 11). A Kruskal–Wallis test showed a significant effect of speed on perceived noticeability (${X^2}_4 = 11.324$, $p < .05$) for the Pincher. This may be explained through slower actuations increasing in intensity more gradually until they

	Pinching	Stretching	Stroking
Pinching	**44%**	44%	12%
Stretching	34%	**54%**	12%
Stroking	27%	10%	**63%**

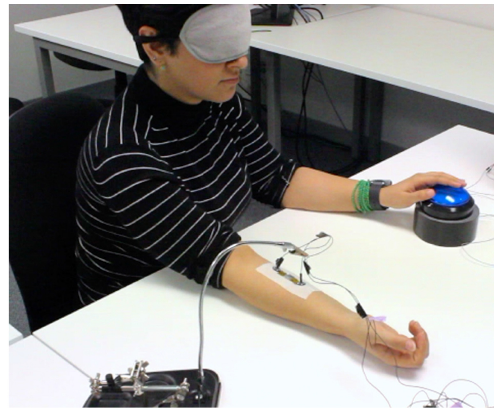


Fig. 10. Confusion matrix of participants' classification of stimulation (left); Perceptual Study Setup (right).

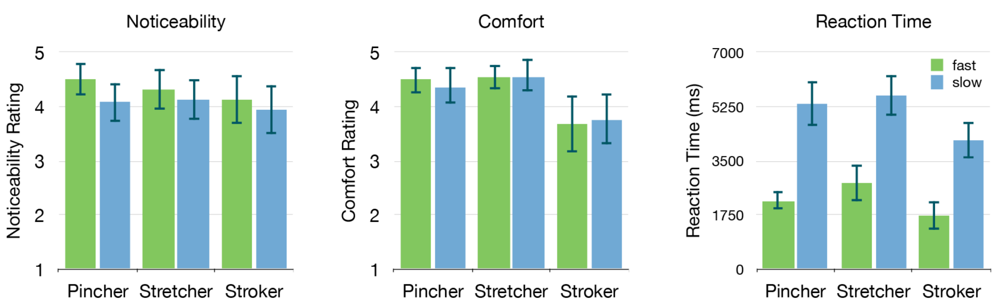


Fig. 11. Noticeability (left) and comfort (middle) rating on a 5-point likert scale and reaction time (ms, right) regarding Pincher, Stretcher, Stroker for both speeds (mean, 95% CI).

reach their peak pulling force. The lower contrast in intensity change could have resulted in a less noticeable sensation. The reaction times show that participants mostly noticed the perception at the end of an actuation (see Figure 11, right).

Comfort: Only three participants reported to feel mild warmth sometimes for the Pincher. The comfort of the devices and their generated sensations was rated on average to be high ($M = 4.23, SD = 0.57$). However, the Kruskal–Wallis test showed that there was a significant difference on the comfort (${X^2}_4 = 38.282$, $p < .05$). A dunn-test confirmed that the *Stroker* was perceived significantly less comfortable ($M = 3.73, SD = 0.85$) than Pinching ($M = 4.43, SD = 0.45$) and Stretching ($M = 4.54, SD = 0.4$). Moving the pointy tip of the tactor on the skin was often associated with less comfortable experiences like "light scratching" (fast stroke, *P*1), "It felt like a centipede walking on my forearm". (slow stroke, *P*6).

Speed and Direction: Participants could identify the correct speed similarly well for all devices (on average 71% correct answers). The direction was most often answered correctly for Stroking (49% correct). Perceiving the direction for Pinching (36% correct) and Stretching (33% correct) showed to be hard for participants. Female participants showed more difficulties to determine the direction. We observed that participants who did not perceive the movement of Stroking well and reported a less comfortable sensation often confused it with Pinching (see Figure 10): "Absolutely pinching! 5! (very confident rating)" (*P*8). The direction of the *Stretcher* was not as perceivable as assumed. We observed that the skin could only be slightly stretched to one side and quickly reached a point at which it was difficult to stretch it further without pulling the other side closer as well. This could explain why the direction was hard to perceive for many participants, as the both-sided pulling could have dominated the gesture of the *Stretcher*. While this needs to be confirmed, conceptualizing a direction appeared to be difficult for the blindfolded participants in general. They often tried to reconstruct the gesture, particularly the direction, using their fingers on the table.

Discriminability: Participants could most easily discriminate Stroking from Pinching and Stretching (See Figure 10). Pinching and Scratching were confused very easily with each other. Stretching was more easily identified correctly as Pinching. We observed that stretching was incorrectly identified as pinching, most of the times (59.18%) when the actuation speed was fast. Also, pinching was incorrectly identified as stretching, mostly (62.79%) when the pinching actuation speed was low.

Overall, the three essential ANISMA skin-deformation devices were well perceivable by participants. We observed that the devices could invoke different associations and participants discriminated most easily between *Stroker* and the *Pincher* or *Stretcher*. While the effect of the rigid area of the *Stretcher* did not have a noticeable effect on the perceived direction, we observed that users often described the location of Nodes without a support of a rigid area as "lifting the skin up" (P1, P3, P5). P3 and P7 associated (only) the *Stretcher* as a "grabbing" gesture four times. We recommend further investigating the effect of the rigid areas on the perception in future studies. As prior work showed, the perceptibility can vary along with the users' sensibility depending on the body shape and location [27, 36]. In this study, we only focused on the user's forearm. In the future, we see many interesting starting points for further explorations of ANISMA skin-deformation devices, including investigating other body locations and testing sequential or parallel actuation patterns using different actuator layouts and parameter settings.

8 EXPERIMENT 3: USABILITY AND SUPPORTED CREATIVITY

We conducted a user study with 12 HCI researchers, who are interested in haptic devices, to evaluate our toolkit regarding its *usability* and its *usefulness* [39]. Specifically, we sought to find out how ANISMA supports users develop expressive and functional skin deformation devices, and learn how the toolkit can be improved.

8.1 Participants

We invited 4 participants from the focus group and 8 new participants to test our toolkit. Overall, 12 HCI researchers participated in the user study (2 females, 10 males), ages $21 - 36$ years ($M = 27$ $SD = 4.22$). All but one had basic fabrication skills with 3D printing and programming Arduino-like embedded systems.

8.2 Setup and Apparatus

The user study took place in a controlled environment, at 22 degrees Celsius. Participants sat in front of a computer (iMac, 4096×2304 Retina, 21.5-inch) with a typical mouse and keyboard, running ANISMA software in full screen (see Figure 12(a)). An ANISMA control unit (an Arduino controller connected to our custom driver board) was connected to a computer via a serial connection and a constant power supply at 9V. Each participant had access to the following hardware toolkit: SMA Modules (springs with diameter-to-elongated length (mm): 1.37–20, 1.37–40, 2.54–20, 2.54–40), Nodes, cone-shaped 3D-printed tactors, connector cables, tweezers, scissors, skin-adhesive tape (PRIMAFIX Plus), and measuring tape. For 3D printing, the PrusaSlicer software 2.2.0 was used to prepare the print job. Participants had access to an Original Prusa i3 MK3S printer with PLA filament (1.75 mm diameter). To print on the skin-adhesive tape directly, the printer's Z-level

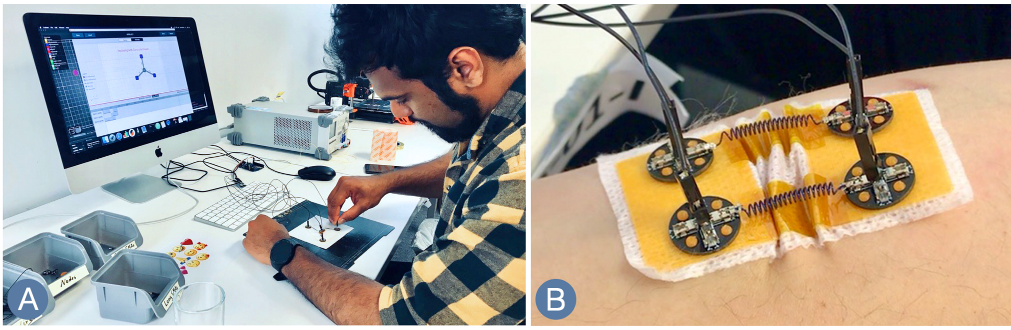


Fig. 12. The user study setup with a participant assembling his prototype in front of the computer showing the virtual design (a); and the *Big Pinch* a participant's design that exploits the strong contraction force of two big SMAs and aims at increasing the actuation frequency of pinching the wearer by actuating one SMA while the other is cooling down (b).

was adjusted to be lifted +0.23 mm above the normal print bed level. Double-sided tape was used to fix the skin adhesive tape onto the 3D printer's bed.

8.3 Method and Procedure

The user study consisted of three sessions. The first session was an introductory session, including a brief demonstration of the ANISMA workflow. In the second session, the participants were asked to accomplish a pre-designed task by following specific instructions set as a quick rehearsal. In the final session, participants were given a creative task in which they carried out the full ANISMA workflow, including designing, fabricating, and programming a device independently.

First session—Introductory: The investigator explained to participants the working principle of SMAs and actuation parameters. Then, he demonstrated the end-to-end workflow of ANISMA by designing, fabricating and programming a directional skin-stretching device from scratch. The device is composed of one SMA spring attached to the skin via two Attached Nodes, one of which has a larger 3D-printed Mount compared to the other. At actuation, the spring compresses, stretching more at the skin underlying the smaller Mount. At the end of the demo, the investigator answered participants' questions.

Second session - Practice task: Participants were asked to create a skin deformation slider, as described in 4.1.

The design task was broken down into a set of simple instructions, such as *In the design view, drag-and-drop two SMAs and connect them from one end.*, *Set the left SMA to actuate for a certain duration*, and *At the end of the first actuation, set the right SMA to actuate faster than the left.* The task was designed to enable participants to interact with all interface features in the design and animation views of ANISMA software. Some design details, like the need to balance the power of the interlinked SMAs to prevent one from overstretching the other, were left for participants to realize from the cues ANISMA provides when a design violates certain thresholds. Participants were encouraged to think aloud during the second and third sessions. The session ended for a participant as soon as they started to be finished.

Third session—Creative task: Participants were encouraged to design, fabricate and program two new skin deformation devices. They were given the following scenario: *Imagine two persons living apart and want to stay in touch via haptic sensations. Using ANISMA, develop two wearable haptic devices that can convey a single emotion or action, similar to emoticons.* Participants were invited to choose any on-body location and explore the use of multiple SMA springs in different layouts. The session ended for a participant as soon as they reported to be finished and did not want to iterate on the design any further.

After the sessions, participants answered two questionnaires: the **system usability scale** (**SUS**) [2] and **creativity support index** (**CSI**) [9]. Then, they were briefly interviewed to capture their feedback and suggestions on how to improve ANISMA. The audio and the computer screen were recorded throughout the second and third sessions. The investigator observed participants and took notes while they assembled and tested the devices.

8.4 Results and Discussion

All twelve participants completed the tasks and presented three functional prototypes at the end of the user study. Overall, participants reported to be satisfied with their designs, they enjoyed the overall experience, and provided feedback on how to improve ANISMA further. In the next sections, we summarize our observations of the design sessions and participants' feedback.

8.4.1 Design Results. The introductory session took between 5 and 10 minutes. Following the introductory session, we observed that most participants (8/12) started operating ANISMA software with confidence. We noticed that whenever a participant was unsure how to execute a design command, they would click and drag different interface elements to help them recall or learn the functionality in the system.

The challenging design step was specifying the actuation parameters of an SMA to control how it compresses. Initially, participants were confused over how the actuation parameters, *contraction duration* and *power*, affect the *force intensity* of an SMA. Often, they assumed that *power* is directly related to *force intensity*: *The SMA control time sequence design was a bit challenging [...] the curve was not very intuitive* (P11, focus group), *I didn't really understand how to control the SMA when I started trying the tool. But the platform made it a good testing bed to learn, play around and see how they actually react over time.* (P2).

At the end of the second session, all participants managed to finish the practice task and design and animate a slider without input from the investigator. On average, participants spent 17.88 minutes (SD = 2.59) on the first task. Upon task completion, two participants asked for additional time to fine tune their designs (e.g., to have a large Effective Movement Area) and test how different design decisions could affect their device.

In the third session, participants' creative devices ranged from simple (stretching the skin using individual SMA Modules) to more complex (multiple SMAs pulling at several Nodes in a timely coordinated way) (Figure 12, 13). On average, participants completed the third session within one hour (M = 64.20, SD = 20.12 minutes). Below we describe five inspiring designs:

- **The Crawler:** P4 (focus group) developed the Crawler to mimic the feeling of a spider crawling up a wearers arm. The Crawler is composed of 6 SMA Modules, 5 Attached Nodes, and 3 Detached Nodes connected as in Figure 13a. To each Detached Node, a 3D printed tactor is connected that strokes the skin. The device was fixed at the forearm. At actuation, the actuators are pulled from the wrist along the arm upward, one after the other. Afterward, the tactors are pulled down to the wrist again. The participant was very excited when he tested the generated haptic sensation on the skin: *Uaahh.. Yes! It really feels like something is crawling up your skin!* (P4, focus group).
- **The Smiler:** Several participants wanted to develop a device that animate the face to recreate an emoticon. P1 designed the Smiler which is composed of 2 SMA Modules, 4 Attached Nodes connected as in Figure 13(b). The device was attached to the face. At actuation, both SMAs contract simultaneously. The lower Nodes with a smaller Mount get pulled toward the Nodes with a larger Mount, and this way lift the corners of the mouth similar to a smile.

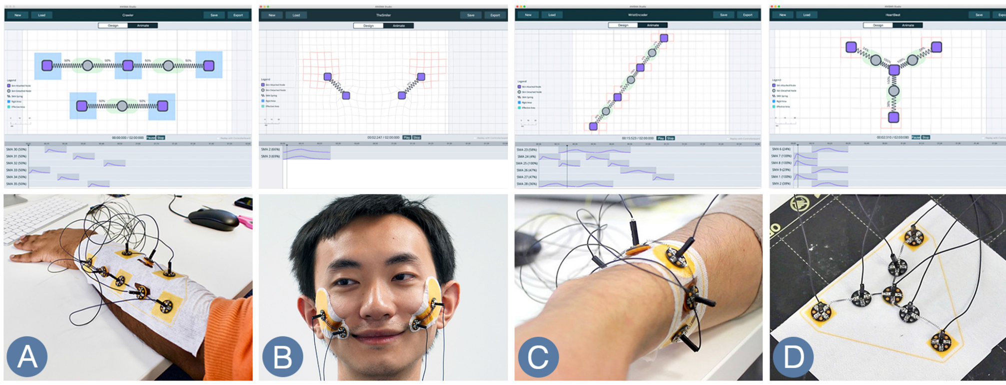
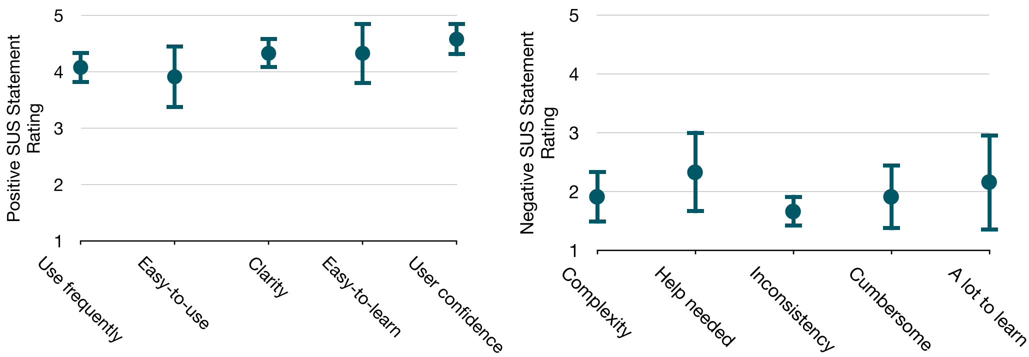


Fig. 13. Selected participant designs from the creative task. Virtual design with actuation sequences (top) and the physical prototype (bottom). From left-to-right: the **Crawler** (a), the **Smiler** (b), the **Wrist-Encoder** (c), the **Pulsing Heart** (d).

- **The Wrist-Encoder:** P10 developed the Wrist-Encoder as a flexible platform for mimicking haptic emoticons. The device is composed of 6 SMA Modules, 4 Attached Nodes, and 3 Detached Nodes connected as in Figure 13(c). A tactor is connected to each Detached Node. The device was attached to the wrist. At actuation, two tactors start stroking around the wrist back and forth. While one tactor strokes slowly, the other performs a fast movement in the same direction. Finally, the third tactor performs one slow and a fast stroke.
- **The Pulsing Heart:** The first design of P5's Pulsing Heart generated strokes on the user's chest, near the heart. Unsatisfied about the sensation, P5 reiterated the design and finally decided to emulate heartbeats using a temporal actuation pattern. The Pulsing Heart is composed of 6 SMA Modules, 4 Attached Nodes, and 3 Detached Nodes connected as in Figure 13(d). A tactor is connected to each Detached Node. During the actuation, the inner SMA Modules contract simultaneously and quickly drag the tactors toward the center while stroking the skin. Afterward the outer SMA Modules slowly pull the tactors from the center to the edges again, generating a smooth long stroke effect.
- **The Big Pinch:** P9 wanted to create a strong pinch effect. Using the big SMAs, she found that they require a long time to cool down (stretch back and be ready to be compressed gain). The final design of the Big Pinch is composed of 2 SMA Modules and 4 Attached Nodes connected as in Figure 12(b). The device was attached on the forearm. At actuation, first, the right SMA contracts. The rigid areas, which connect the Attached Nodes at both sides, squeeze a pinch. When the right SMA is cooled down half way and releases the skin, the left SMA contracts. The skin is squeezed again and the pattern repeats. This way P9 increased the actuation frequency of a strong pinch.

The power and limitations of animation—Participants were positively surprised how well the software simulated the behavior of their devices: "*[...] the simulation already gives a good approximation about real actuation which is fascinating to see.* (P5)". They reported that the animator helped them explore the effects of different actuation parameters on the behavior of SMAs and accordingly fine tune their designs to become more effective. In certain cases, however, the animation did not match the actuation behavior on the skin. Two participants observed that the lack of accurately modeling the skin friction and stiffness in ANISMA's animator, led to overestimating the range of movement of a Detached Node dragging on the skin. Yet, participants relied heavily on the animator during all design tasks and were mostly satisfied with the end results.



(a) Subjective rating of the positive SUS statements. (b) Subjective rating of the negative SUS statements.

Fig. 14. Mean subjective ratings of the SUS statements on a 5-Point Likert scale (1 Strongly Disagree–5 Strongly Agree) with 95% CIs. The overall SUS Score depicts $M = 78.13$ ($SD = 12.84$).

A safe environment to test and build design confidence—The devices above demonstrate how ANISMA supported participants of different experience levels to develop multi-SMA devices that run relatively long actuation sequences. After the practice task, in the second session, participants were more comfortable and highly motivated to build their own devices. They used the system to ideate, evaluate initial designs and explore new ideas. Interestingly, during the creative task, participants' focus shifted from how to operate the software toward thinking of application ideas and the haptic sensations they wish to generate. With a few elements, four SMA Modules and a few Nodes, participants designed unique and expressive devices for compelling applications. ANISMA software allowed participants to familiarize themselves with SMA actuators within a safe sandbox. For example, the *Big Pinch* demonstrates how participants understood the different properties of SMAs and discovered, through iterative design and animation, how to overcome certain limitations of single actuators (see Figure 12).

Finally, during the fabrication and assembly step of the creative task, one participant mixed up the wiring of their device such that one of the SMAs in that device was overheated and permanently damaged. This incident gave us an insight on how we could extend ANISMA's tools to support users wire their devices effectively and safely.

8.4.2 Usability and Creativity Scores. Participants rated overall usability of ANISMA at $M = 78.13$ ($SD = 12.84$) (SUS score range $0 - 100$). According to a survey covering 273 SUS studies, our score lies above the mean of 69.5 and would fall between a "good" and "excellent" usability rating [3]. However, it is hard to compare our SUS score reasonably with other artifacts, as our toolkit significantly differs from many systems that have been rated using the SUS score before: it comprises a GUI, a fabrication process and the assembly of hardware components. Nevertheless, we hope the overall score will serve as a reference for future toolkits that undergo a usability test and deal with similar elements.

Figures 14(a) and 14(b) summarize the results of the SUS questionnaire. Notably, the 8 participants who had no prior experience with SMAs, rated the system's usability similarly high $M = 78.44$ ($SD = 15.23$) as participants who had participated in the focus group $M = 77.50$ ($SD = 7.95$). In addition, most participants agreed that they would like to *use the system frequently* $M = 4.08$ ($SD = 0.51$). ANISMA's *clarity* and *ease-of-use* were also rated above 4.0. The rating of *easy-to-learn*, *need help*, and *a lot to learn* cue that the interface can be improved to support first time users.

Table 1. CSI Results for the Individual Scales

Scale	Avg. Factor Counts (SD)	Avg. Factor Score (SD)	Avg. Weighted Factor Score (SD)
Results Worth Effort	3.00 (1.28)	16.00 (1.28)	47.67 (20.23)
Exploration	4.08 (0.90)	15.50 (2.47)	63.00 (16.89)
Collaboration	0.92 (1.00)	14.83 (2.04)	13.58 (14.54)
Immersion	1.75 (1.22)	14.25 (3.41)	24.50 (18.07)
Expressiveness	3.17 (1.27)	16.00 (2.45)	51.67 (25.30)
Enjoyment	2.08 (1.56)	16.75 (2.63)	36.00 (27.09)

Exploration and *Expressiveness* scored highest. The Avg. Factor Counts column shows how often participants prioritized a scale within the paired-factor comparisons. The Avg. Factor Score indicates how high the different scales were rated independent from the priorities (range 0–20). The overall CSI score depicts 78.81 (range 0–100) and is calculated based on the Avg. Weighted Factor Scores.

The supported creativity by our tool was rated reasonably high by the users, with a CSI of 78.81 (range 0–100) which is comparable to a *C+* grade. Participants from the focus group showed a slightly lower CSI score (78.25) compared to other participants (80.58). While the expressiveness score was lower for focus group participants (45 compared to 55), they rated the exploration higher (66 opposed to 61.5). Immersion was rated notably higher by the new participants (30.5) compared to the focus group participants (12.5). The overall results for the CSI scales can be found in Table 1. Exploration and expressiveness scored highest for the weighted factor scores and were perceived to be the most important by participants.

8.4.3 User Feedback. Participants were very enthusiastic about using the toolkit in the future for different application scenarios: *I am really amazed by the design. I would use this system and try out various things for sure.* (P7, focus group), *I see a lot of potential for VR/AR applications. E.g., remote interaction.* (P9), *I would explore different haptic sensations to communicate with others.* (P6). Participant P3 moreover wanted to investigate different materials and attachments (like metals, brushes, sponges...) for the Detached Nodes to induce different sensations. In the user study, our toolkit only provided one stiff tactor as an object that could be attached to a Detached Node. Several users also mentioned potential application areas that go beyond the scope of our toolkits, such as prototyping art installations or shape-changing interfaces. One user asked whether the toolkit could be extended for 3D structures and animated objects.

Suggested improvements—Overall the users did not see critical issues that limit exploring skin deformation applications, however, they highlighted potential extensions that could improve animation and simplify certain prototyping steps, such as defining a motion path for Detached Nodes. We discuss some potential ideas and other usage scenarios of our toolkit in the Future Work and Limitations section.

Effective skin deformation and Noticeability—Even though this was not the focus of the toolkit evaluation in this experiment, most participants reported that they could clearly feel the stimuli induced by their devices; in fact, devices like the Big Pinch were able to induce very strong skin deformation.

9 LIMITATIONS AND FUTURE WORK

ANISMA depicts a compromise in simplifying the prototyping process of skin deformation devices based on SMA actuators and providing an expressive platform to explore diverse designs. Hence, the developed system still offers several opportunities for improvements. In the following, we describe several existing limitations of our system and discuss promising possibilities to extend our toolkit in the future.

9.1 Actuation Model and Simulation

Our actuation model shows to predict the SMA heating and cooling characteristics good enough to estimate a safe actuation interval that prevents users from easily damaging the actuators. However, it still comprises a high-level model that has several limitations. Our model was derived and tested at a constant room temperature of 22 degrees Celsius. We cannot guarantee that the model holds true in environments with drastically different temperatures or temperature variations. For example, slower cool down and the resulting heat accumulation might change actuation patterns or even damage the actuator. More investigation on the behavior of the model under different temperatures and subsequent changes to it are needed.

Additionally, our model seems to break when predicting the actuation behavior for low currents, such as around $0.2A$ for the small SMAs. While the simulation still predicts motion at low currents, the SMA does not contract in reality. We believe this has two reasons: (1) We scale down the actuation curve recorded at higher current flow, which may not hold at low power levels, as the ohmic heating may not suffice to induce a phase transformation and cause the SMA to contract. (2) The simulation yet does not model the spring resistance itself. In our simulation two antagonistic SMAs can easily pull a shared Detached Node, in reality, there is a minimum force required to overcome the spring resistance of the antagonistic spring.

9.2 Feedback-Loop and Cooling System

Within various of our interviews, the interviewees stated that they believe that a cooling system and a feedback loop could help overcome the most significant drawbacks of SMAs, namely low controllability and low actuation frequency. While such a system's development was out of our scope, we agree that our toolkit would have largely benefited from both as it would, for example, allow maintaining a certain force level for a longer time. However, we recognize that a cooling- and feedback loop system is particularly challenging to develop as it must comply with the compelling characteristics that make SMAs applicable for wearable applications, such as a compact and flexible form factor.

9.3 Inverse Design Approach

At the moment the user needs to manually specify the actuation of individual SMAs to pull a Node in the desired direction in the software. Our user study participants showed interest in directly manipulating the Nodes by dragging them along the desired movement path similarly as proposed by Schneider et al. [64]. The software could then automatically calculate the needed control pattern of the connected SMA actuators. While the implementation of this method appears to be a compelling task with the current limitations of the actuators' actuation frequency and latency, it could simplify the animation of skin-deformation devices drastically. Assuming that these limitations will be solved in the future, we envision an ideal future system that only requires the user to describe the desired end-effect on the skin, and then derives the needed physical elements, layout, and actuations automatically. A future tool could furthermore increase the intuitiveness and design interactivity by using the skin as input space for the modeling process and displaying the simulation directly on the user's body before the fabrication similar to [22, 23, 32].

9.4 Node Attachments and Rail Systems

For our user study, we had only prepared one type of 3D printed tactor that could be easily plugged into a Node. This resulted in some users asking whether they could also attach different objects. In the future, we intend to investigate different tactors to render smooth and rough textures on the skin. We also observed that the dragged tactors were not always evenly pressed onto the skin while being pulled. Using a rail system on which the tactors slide along would ensure more even stimuli along predefined paths and render shapes more robustly.

9.5 Extending ANISMA Software

We see several opportunities to extend the software environment in the future. By adding more types of SMA actuators users could compare a greater variety of actuators from different manufacturers. Providing the users with basic building blocks, such as the slider device, could further simplify the exploration of complex devices. At the moment the user manually has to start the actuation sequence in the animation view. Several users asked for a loop functionality to automatically repeat an actuation sequence. In the future, external events could trigger actuation sequences, which would allow the integrating actuation sequences of ANISMA devices into interactive applications.

9.6 3D Structures and Shape-Changing Interfaces

While we believe that our toolkit opens up a new perspective on prototyping two-dimensional skin-deformation devices with SMAs, we see great potential in extending it to more advanced mechanisms and 3D structures in the future. Combining our toolkit with auxetic structures [66] and metamaterials [30] could enable new exciting devices that leverage novel haptic experiences on the skin. Several participants commented that they see potential in using the toolkit for purposes apart from skin deformation applications. We believe that our tool could also be used to animate 3D structures in other contexts or to design shape-changing interfaces. In fact, interested people could use the toolkit in its current form to animate passive objects, as the adhesive tape allows them to attach the prototypes to various kinds of surfaces easily.

10 CONCLUSION

In this article, we presented the system design, workflow and evaluation of ANISMA, a software and hardware toolkit to prototype on-skin haptic skin deformation devices using SMAs. Our system addresses challenges that HCI researchers face when working with SMAs for wearable haptic devices. We performed a technical analysis of the essential ANISMA skin-deformation devices and verified their perceptibility on the forearm. Our evaluation comprising a user study with 12 researchers showed that ANISMA embeds expert knowledge that enables novice users to easily start working with SMAs. Using our tool participants showed to be able to creatively explore haptic applications, involving the process of designing, programming, and testing more advanced skin deformation devices with multiple SMAs.

Besides discussing more advanced prototypes that can be facilitated with our toolkit, we mentioned limitations along with future improvements of our toolkit. Finally, we showed up future opportunities of using our toolkit, including use cases beyond skin deformation applications, such as for animating objects, and shape-changing interfaces. We hope that our toolkit contributes to increasing the accessibility of SMA actuators in the context of haptic skin deformation applications for HCI researchers and opens up new perspectives on possible ways of integrating SMAs and exploring haptic applications with the soft actuators.

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