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Master's Thesis

Academic Year 2019

Skin+:
Modular Programmable Skin

Keio University

Graduate School of Media Design

Feier Cao

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Feier Cao

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Abstract of Master's Thesis of Academic Year 2019

Skin+: Modular Programmable Skin

Category: Science / Engineering

Summary

The skin is a natural interface between the inside and outside of our body. It holds us into shape, as well as it shapes the way we behave. Wearing clothes would significantly lower the interactivity of this interface, which as a result limits us into a small area of the exposed skin such as fingers, palms, and face for good interactivity. This research is focused to create a new "organ extension" of our skin by modularizing the haptic interaction of the covered skin such as upper arms, shoulders, back, and calves. This new extension would allow creating a transparent medium beyond the worn fabric and would reshape our skin function by augmenting its haptic sensation.

In this research, the proposed *Skin+* is an approach of an on-skin integrated haptic layer, which would create a seamless channel with our physical surroundings. It allows augmenting touch sensation through the mechanism of the combination of shape-memory alloy (SMA) actuators and the modular auxetic structures. This research has potential applications in creating new forms of reprogrammable haptic modules utilized on a wide area of skin for haptic augmentation in both virtual reality (VR) and physical environments.

Keywords:

Haptics, Second Skin, SMA, Augmented Perception, Auxetics

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Chapter 1
Introduction

In this chapter, the background and the brief of the research will be explained. First, the history of skin evolution, the potential of the skin future will be discussed. Secondly, the research approach and the research purpose of this thesis will be introduced. Last but not least, the thesis contribution and the thesis outline will be shown.

1.1. Evolution of Human Skin

When you look at a person, you will notice his or her skin immediately. The skin serves as the most outstanding part of the human phenotype. Since the last common ancestor of humans diverged from chimpanzees, human evolution took place and went through several morphological, developmental, physiological, and behavioural alterations [4].

The skin evolution also occurred along this period. Shifting from hairy to mostly hairless, the skin adjusts the body temperature and keeps the body cool [5]. After lessening body hair, a habit of clothing on the skin has been gradually developed by the human to balance the body temperature towards diverse climates and altitudes and also protect the body itself.

Furthermore, with piercing, branding, tattooing on the skin, humans reveal significant ownership of the body as well as show unique self-expression to others.

As the most extensive and heaviest organ of the body, the skin has been overlooked in human evolution for long years. We cannot help but wonder what our skin will be like or what kind of new usage or function our skin will have in the future, where the research is aimed.

1.2. Future of Skin

The skin has long been portrayed as an organ that enwraps everything we represent as an individual. Instead of caging us, the skin does create, regulate, and transmit contacts with the external environment. Considering from the future of the skin, the fashion designer Tamae Hirokawa developed a "Skin Series" which utilizes no-sewing knit to show the picture of the skin in her imagination [1.1], which is the way she pictures the skin in the future.

(PHOTOGRAPH COURTESY OF SOMA DESIGN [6])

Figure 1.1 Skin Series *by Tamae Hirokawa*

1.2.1 Skin, Our First Point of Contact

When people think of the skin, not one but many skin functions will come into mind. The skin has been regarded to be a protective organ that keeps the human from harmful environmental influences (physical, chemical and microbiological) and is famous for keeping the balance of body temperature, electrolyte, and fluid. One of the crucial functions of the skin which connect us to the external world is the sense of touch.

Sense of touch has been a great modality for us to communicate with the outside. We perceive the world mainly through five basic senses: sight, hearing, smell, taste, and touch. Among those five modalities, visual and auditory perception are highly robust ways to interact with the outside of the body. However, it is universally considered that the sense of touch is the first sense that humans develop to discern the tangible space in an active manner [7].

As the largest organ of the human body, the skin not only acts as the defensive barrier of the body but also as a sense organ with a vast surface area as well. The skin enables us to perceive the ambient environment naturally, due to its capability to acquire diverse tactile sensations such as pressure, vibration, temperature, and pain.

The perception loop is that for example, when a person touches a thing, the cutaneous receptors will receive the stimuli and transmit signals to the brain to perceive the tactile sensation. That is the way we perceive a thing through our skin.

1.2.2 Skin Potentials

The skin can detect critical information about the ambient environment and the objects touched. A single touch can be informative.

However, the contact restricts this ability to the extent that we cannot touch or feel a thing at a distance without reaching for it physically. Therefore, usually, we prefer to perceive the objects we can directly reach in a haptic manner; but for the objects that we cannot reach, we mostly rely on sight and other sense organs.

The overuse of seeing and hearing adds burden to the eyes and ears, resulting in damaging their ability in a sense. It often happens that people experience hearing damage when they are exposed to music for a repeated long time with a high sound level, which shows that we better have a support plan because of our immoderate use of the sensory organ.

It is also not uncommon that eyestrain or asthenopia happens after excessive use of the eyes such as reading and using computers for a long time. Visually intense tasks cover a large percentage of our life. We surf on the internet to gather information, navigate on the road through constantly comparing the map application with the real world, send messages to communicate with people at a distance and watch movies together with friends or lovers to share the emotions.

The capability to see is becoming almost indispensable for our life quality, while a growing number of people are suffering from refractive errors. Some people can barely see things at a distance without glasses; others suffer from discerning close objects. Besides, people tend to ignore other things when they are doing some visually intensive tasks. Therefore, the eye-free interaction has been researched for long to take responsibility for some parts of the visually intensive tasks and relieve the burden of the eyes.

The skin, with the large surface area and panoramic sites onto the body, has a great potential in this field. It can be and will be comprehensive support to our other senses. So we cannot help but wonder what will happen if we can reprogram our skin to expand its use and reach.

1.3. Skin+ Approach

In this thesis, we present Skin+, an organ extension, an approach to a modular programmable on-skin extension for haptic augmentation.

Skin+, Integrated Haptic Module

This proposed Skin+ is a novel on-skin haptic interface integrated through developable Skin+ modules that are pliable to the skin. Skin+ can be assembled and deployed on different body geometries, such as upper arms and calves. One Skin+ module contains a dynamic linkage structure. In the thesis, we use a mechanical structure with a set of SMA micro-spring actuators to present soft actuation.

The Skin+ modules can be directly put onto form-fitting cloth to have independent movement to have single or multiple actuation patterns.

Skin+, New Sense

Imagine you are in the dark. You can barely see anything but you can perceive.

We picture Skin+ as a new organ, a new sense to the human. Although in the thesis we only introduce limited body sites, we firmly believe that Skin+ will be able to apply to the whole body as a completely intuitive interface for the human in the future as shown in Figure 1.2.

Differing from past haptic devices, it aims to serve as a thin, intuitive, integrated haptic module for the human. We have the vision to control and program different area of our skin for a new way of perception. In the thesis, we take spatial perception as an example to show the capability of Skin+ system.

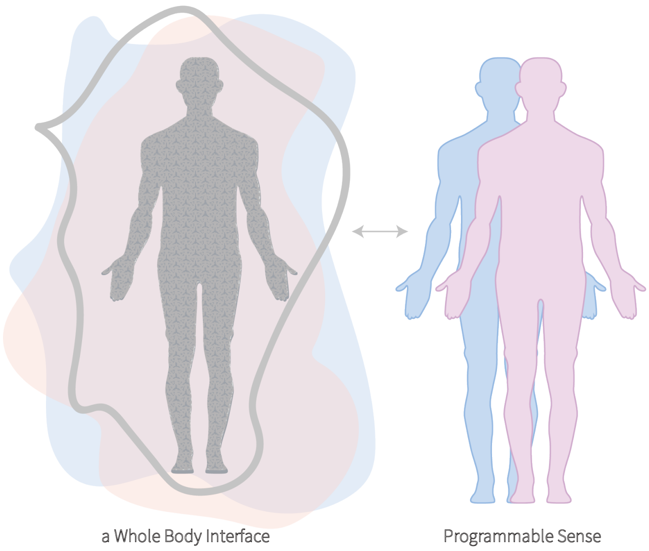


Figure 1.2 Skin+, a Whole Body Interface

1.4. Research Purpose

We propose Skin+ as a novel on-skin interface for haptic augmentation. In this section, we outline research goals for Skin+ system from a human-computer interaction perspective, which can serve as guidelines and criteria for this research and also future works.

1. *Programmable:* To have multistage control over the *Skin+* system to let users acquire position, direction and intensity. For example, the user can get notified if someone is coming nearby.

2. *Modular:* To have consistent modular designs for the whole *Skin+* system and developable for a combination of multiple modules.

3. *Customizable:* It is possible to generate a 2D haptic design of *Skin+* procedurally for a large area of skin that fits into different body parts such as upper arms and calves.

4. *Lightweight and Flexible:* In contrast to haptic devices applied in Virtual Reality environments which is normally bulky, we put our efforts on a thin and flexible haptic device which can seamlessly let users have the intuitive sensation and pliable to various body sites.

1.5. Contributions

In this thesis, we contribute Skin+ a modular system for haptic augmentation:

Skin+ introduces a novel lightweight on-skin interface that serves as an expressive display to mediate touch sensation. In this thesis, we describe the design and implementation of Skin+ and its usability in the daily scenarios. We use modular structures to build this programmable tactile interface. The combination of shape-memory alloy with a modular structure enables a lightweight haptic device that can be worn seamlessly on top of our skin. The contributions of the thesis are listed as follows:

1. Lightweight on-skin modular interface.

2. Shape-memory-alloy-based (motorless) actuator for friction sensation.

3. Perception-augmentation in bug crawling for directional actuation.

1.6. Thesis Outline

This thesis outline is shown as follows:

1. Chapter 1 will introduce the evolution of skin and potential of future skin. Then we will have a brief introduction for our Skin+ approach and pinpoint the research goal and our contributions, as mentioned above.

2. At the beginning of Chapter 2, human skin function will be addressed. Related works both in fashion and research will also be presented in chapter 2. At the end of chapter 2, thesis contributions will be stated.

3. Chapter 3 starts to explain Skin+. First, the ideation of the Skin+ will be introduced. Then the Skin+ system and the implementation with modular prototypes will be shown. Also, possible variations and applications of those have been presented in the same chapter.

4. Chapter 4 demonstrates the evaluation of Skin+, which covers three stages: a pretest, a psychophysical study, and a user study.

5. In the last chapter, the conclusion of the whole thesis will be given.

Chapter 2
Related Work

In this chapter, related work will be categorized into four sections. First of all, we talked about human skin functions. Second is the second skin idea developed in fashion and research fields. Third, previous applications through haptic augmentation are shown. Last but not least, the existent mechanism for haptic augmentation is discussed.

2.1. Human Skin Function

In the evolution of bats, the skin has evolved into owning an additional function: formation of a wing membrane utilized in powered flight. The skin can generate lift and thrust and give locomotion [8]. The snakes' skin alone can support snakes to have rectilinear locomotion, where the skin moves relatively to the fixed skeleton [9].

When it comes to skin function, we can think of not one but many functions as shown in the Figure 2.1 [1]. Human skin, universally considered the largest organ in the human body, has many functions. You may not often think of the skin as an organ. The skin is made of tissues as a whole structure to run critical functions.

2.1.1 Skin Layer

The integumentary system is made up of the skin and its accessory structures.

To help us understand more about human skin function, we will introduce the real layers of the human skin. The image shown below is the analogy illustration for the skin. As shown in Figure 2.2, the skin consists of three layers (from top to bottom) [10] :

- Protection from the environment
  - Mechanical, keep the form and internal organs in position and away from damage
  - Chemical, internal homeostasis in water and land (barrier)
  - Physical: UV (melanocyte on human)
  - Keep moist (amphibian) and oily (sebaceous gland)
  - To be worn off
  - To heal and regenerate (cytokines)
- Defense
  - Exoskeleton (arthropod)
  - Armor (turtle, armadillo)
  - Spiny appendages (porcupine quills)
  - Inflammatory response (prostaglandin, etc.)
  - Immune function, with memory of previous stimuli
- Weapons
  - Sting cell of hydra and jelly fish
  - Claws
  - Poisonous glands
- Communication with outside organisms
  - Display of messages (pigment pattern, painted skin of human)
  - To mark territory
  - Pheromones for sexual attraction
  - For pack behavior coordination
  - To scare enemies away
  - To mimic
- Communication with inside organs
  - Sense the environment (human skin, mouse vibrissa)
  - Tactile or thermo senses go in through nerves
  - Endocrine-like function through secretion (neuro-endocrines, endorphin, growth factors, etc.)
- Respiration
  - Insects
  - Some frogs
- Chemical reaction
  - Vitamin D
- Locomotion
  - Swim (tentacles of hydra, jelly fish and octopus; tube feet of sea cucumber)
  - Crawl (belly scale of snake)
  - Glide (skin flap of Pterosaur, bat)
  - Fly (feathers)
- Thermoregulation
  - Hairs (mammals)
  - Sweat gland
  - Dermal blood vessels
  - Feathers (feathered dinosaurs, birds)
- Progeny bearing
  - Skin flap in toads and abdominal pouch in kangaroos
  - Mammary glands in mammals

Figure 2.1 Skin Function [1]

- Epidermis

  The epidermis is the outermost layer of skin, made of closely packed epithelial cell. It serves as a waterproof barrier and creates our skin tone as well.

- Dermis

  The dermis lies beneath the epidermis, which is made of dense, irregular connective tissue. It contains tough connective tissue, hair follicles, and sweat glands.

- Hypodermis

  The hypodermis is composed of fat and connective tissue.

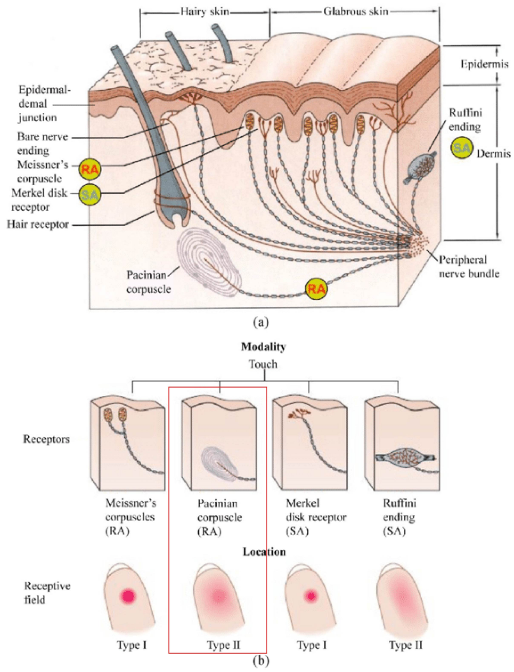


Figure 2.2 Skin Layer with Mechanoreceptors [2]

2.1.2 Sense of Touch

We mentioned in Chapter 1 that, sense of touch is one of the key function we focus on. If we picture the skin in the future, it is crucial to understand the sensory properties of biological skin because the mechanical properties of skin have major effects on its sensory properties. There are various kinds of receptors lying in the skin. The receptors convert information where voltage spikes happen, which is called action potentials. The tactile sensation can be captured by thermoreceptors, mechanoreceptors, and nociceptors.

In this research, we focus on the mechanoreceptors, which include the ability to measure innocuous mechanical cues. As shown in Table 2.1 [11], there are four types of mechanoreceptors to detect the stimulus onto the skin: Merkel disks, Meissner corpuscles, Pacinian corpuscles, and Ruffini endings. They not only measure forces on diverse timescales but also with diverse receptive field sizes (which means the area of the skin giving a response from the mechanoreceptors).

Slow adapting receptors, SA-I and SA-II, react to static pressures, a sustained signal responsive to a sustained stimulus. Fast adapting receptors, FA-I and FA-II, react to dynamic forces and vibrations. Located close to the surface of the skin, SA-I receptors react with high sensitivity. They have high density in fingertips, which is useful for us to tell object shape and texture. Located deeper in the skin, SA-II receptors can detect skin stretch, which serves well for proprioception. FA-I receptors detect low-frequency (5–50 Hz) stimuli, which is important for object manipulation and texture discrimination. FA-II receptors detect high-frequency vibrations (up to 400 Hz) over large areas, and are important for texture discrimination and slip detection.

In the thesis, we focus more on haptic sensation over a large area. Therefore FA-II receptors are more concerned to be related to this work.

*Note that here we only talk about the mechanoreceptors under the glabrous skin.

2.2. Haptic Augmentation

In the domain of haptic augmentation, there are some well-established works in research fields.

Table 2.1 Mechanoreceptors in the Skin

Mechanoreceptor	**Touch**	**Stimuli**	**Position**	**Sensing Property**
Meissner's corpuscle	light touch	constant changing	shallow	stroke, fluttering
Pacinian's corpuscle	deep touch	constant changing	deep	vibration
Merkel's disk	light touch	sustained	shallow	pressure, texture
Ruffini's ending	deep touch	sustained	deep	stretch

2.2.1 Navigation and Notification

Je *et al.* [12] utilizes a solenoid on the finger for eye-free navigation. The pinching pressure of a finger-wrap style movement is directly exerted on the finger. Kajimoto *et al.* [13] presented a haptic device that manipulates the waist-type Hanger Reflex through pneumatic actuators. Hanger Reflex is a phenomenon that skin deformation produces an illusory force and involuntary rotation of the body parts. Therefore, the meaning of the force feedback is not necessary for interpretation of, which creates an intuitive interface.

Peiris *et al.* [14] 's work presents a bracelet which made thermal feedback around the wrist for haptic notification.

2.2.2 VR

Ultrahaptics [15] uses ultrasound to create the haptic feedback in the air, which can be applied to the feedback for the interface in VR environments.

In Minamizawa *et al.* [16]'s work utilizes servomotors to create a vertical shearing force to present a weight sensation to simulate gravity in VR environments.

The Synesthesia suit [17] presents a whole-body haptic suit in VR video games. It consists of not only the vibrators but also the LED to visualize the users' experience.

2.2.3 Perception Augmentation

Haptic Radar makes it possible for a person to get a sense of touching objects that are not in direct contact with the skin, such as microbes of cilia, insect antennae, and mammals moths [18].

In another work called “echo”, the clothes themselves emit a signal, recognize the space by measuring the distance [19]. The reaction returns to users as vibration. Through the “echo” were the clothes themselves transmit and feel the distance to space. Users can perceive ways of feeling space in a new form.

An interesting work called “Ants in the Pants” [20] creates a wearable tactile display using motors to reproduce the thrilling sensation of being touched by an insect’s antennas and legs. The users can perceive the ants crawling over the arm.

2.3. Second Skin

The second skin idea has been studied from both fashion and research perspectives.

2.3.1 Second Skin in Fashion

“Second Skin” is a term often mentioned and discussed in fashion. Human has a long history of decorating their skin.

One fashion artist to be mentioned is Rachel Freire. She created a rain-coat-like “Embodisuit” which serves as an information ecosystem for users to map signals to various body sites [21]. For example, when it rains outside, your shoulder will feel cold. The work utilizes body geometry to interpret the given contents. Moreover, the next work she developed is “Second Skin”, a full body functioning garment via the stretchable e-textile, which also embraces the body shape [22]. The work creates a platform, giving great potential in creating on-skin interfaces.

Behnaz Farahi’s work “Caress of the Gaze” is another excellent work worth mentioning [23]. She designed and fabricated a 3D-printed half body garment, which is called the 3d body architecture. A small camera hidden in the garment captures and recognizes people’s gaze. Then the garment will be activated and have a deformation of the whole shape through the gaze. The work explores the possibility of interaction between people via clothing. It also shows great potential in creating social bonding.

2.3.2 Second Skin in Research

Second skin has also been a prevalent keyword in the research field.

A second skin has been created by MIT scientists for individuals. The novel material is a silicone-based polymer which could be applied on the skin as a thin, imperceptible layer, mimicking the mechanical and elastic elements of healthy, young skin. It can safeguard and tighten the skin and smooth wrinkles momentarily

ElectroDermis pictures the electronics in the future can stick to the human body with the notion of impermanence, unlike tattoo and implant. They offer an approach to create stretchable skin-like wearable bandages on the body using silicone [24].

BioLogic [25] is proposed by Tangible Media Group in MIT Media Lab. Considering beyond the second skin, the team created a bio-skin with the nano-material which can be actuated by humidity as shown in Figure 2.3. When the heat and sweat go over a certain value, the suit will have those “cells” open; when the heat and sweat go down, the suit will have those “cells” close. It best fits the scenario of dissipating the heat of the body when a person feels too warm. The control of the actuation is greatly dependent on the humidity of the environment.

Anusha’s Tacttoo introduces a feel-through tattoo on the skin for electro-tactile interface [26]. It shows the potential both in sensing and actuating. The haptic tattoo is managed to be made dramatically thin to lessen the awareness of users’ wearing it. It is delicate and amazing work.

Weigel proposed iSkin [27], which also adds a touch to the potential in customizing the skin in sensing scenarios. This tattoo-like interface is capable of having designed patterns or drawings to have self-expression as well as contributing to the body input, which acts as a sensing tool.

Kajimoto *et al.* [28] proposed a projection-based interactive second skin wearable [28], which provides vibrotactile sensation. It is responsive to a projected light pattern. The projected light indicates where the feedback happens, which improves the experience of the users as well as the audience.

[Photographs by Rob Chron [25]])

Figure 2.3 BioLogic, Living garment "Second Skin"

2.4. Soft Actuators

There are a lot of soft actuators applicable in the haptic field. In this section, three main types of soft actuators will be mentioned: pneumatic actuators, dielectric elastomer actuators, and SMA actuators.

2.4.1 Pneumatic

Pneumatic actuators have become a prevalent choice when it comes to soft actuators.

Pressure-based

This type of actuators often utilizes air pressure or water pressure to generate soft actuation. The pneumatic actuator mainly consists of a diaphragm, which helps to convert the energy to a certain type of mechanical motion. The control signal could be small. The system connected to the diaphragm will act as an amplifier to present the motion. The pneumatic system keeps the air in, allowing air pressure to force the diaphragm to move the connecting element to have a specific motion designed.

Pneumatic Actuators for Haptic Interface

Feng *et al.* [29] created an air-pressure-based haptic display, where groups of speakers are used to push air to inflate and deflate the airbags fixed on the fingertip. The airbags are 3d printed using two kinds of materials. The base material is tough, while the top material is flexible. The combination enables the actuation to happen. This work can create a water-like sensation in Virtual Reality scenarios.

Limitations

Although the pneumatic actuator demonstrates great potential in haptic fields, due to its bulky devices to generate pressure, it does not perfectly fit the second skin theme, where the actuation system should be as lightweight as possible.

2.4.2 Dielectric

The dielectric actuator is another choice for soft actuators.

Dielectric Electroactive Polymers

Dielectric EAPs are smart materials where electrostatic forces between two electrodes cause actuation, squeezing the polymer. With the capability to stand high strains, dielectric EAPs are originally a capacitor, which alters its capacitance when a voltage is applied. Due to the electric field, it enables the polymer to compress in thickness and the meantime expand in the area.

A high actuation voltage is necessary to produce high electric fields, which means hundreds or thousands of volts. However, it only consumes meager electrical power. In short, the essence of this type of actuator is to use high voltage to apply on two electrodes to let it press the elastomer film to elongate.

Dielectric Actuators for Haptic Interface

There are a lot of commercial materials for dielectric actuators such as E-rubber.

E-rubber by Toyoda Gosei[1] has also been tested for this project. The rubber is pliable to the skin. High voltage and low current with visible movement are good; but, it is hard for the researchers to customize by themselves in the current stage. So it is not used as a research method in this project.

Limitations

While the dielectric actuator is pliable and gentle to the skin and the actuator itself is lightweight. Still, the whole system is not safe or mature enough for the body due to the high voltage. Also, the high voltage needs to be generated through a bulky device such as a high-power amplifier.

2.4.3 SMA

Shape-memory alloys have been long studied as a type of lightweight, soft actuators. The nitinol shape-memory alloy has been carefully chosen as a final method for this thesis. Therefore, in this subsection, it will be narrated more in detail compared to other methods.

Shape Memory Effect

Shape memory effects have been found in nitinol. The shape memory effect in nitinol arises from the two forms of crystal structures dependent on the temperature with dramatically diverse properties: martensite and austenite. This results from twinning at the very high degree in martensitic nitinol, where "a partial atomic spacing" rotates the atomic bonds, which turns out to be floppy. Therefore, if the nitinol turns to martensitic, these bonds will be able to move around without breaking, demonstrating the ability to be deformed in a macro perspective [30].

This effect presents that the metal will remember the shape at a certain temperature. The SMA can be categorized into one-way and two-way.

- For the one-way SMA, the SMA will remember the shape at a higher temperature and become rigid (austenite) when it reaches the temperature. When

1 E-rubber, Toyoda Gosei, https://www.toyoda-gosei.co.jp/e-rubber/

it cools down, it will not change the shape automatically but will become not stiff (martensite) from the material aspect.

- As for the two-way SMA, the SMA will remember two shapes at a lower temperature and a higher temperature. When it heats up to the higher temperature, it will remember one shape; and when it cools down to the lower temperature, it will remember the other shape.

Actuation Methods

As mentioned above, nitinol is likely to alter phases at some specific temperatures. Therefore, whatever you do to alter the temperature may have the capability to actuate nitinol. One of the popular options is to apply direct heat, which may come from sunlight, warm water, or just simply the change in air temperature whichever way you wish. Another choice is to apply current to heat the SMA actuator to its transition temperature to initiate the transformation process.

For the convenience, the SMA is usually driven by current due to Joule heating effects. We can accurately calculate how much current should be applied to activate an SMA actuator within the amount of time expected. This does not take into consideration radiant, conductive, or convective cooling, and therefore, it is for short cycle periods (2 seconds or less) [31].

1. The Joule heating equation, $P = I^2R$ (P is power, I is current, and R is resistance).
2. Resistance, $R = \rho L/A$ (ρ is resistivity, L is the length of the mechanism, and A is the cross-sectional area).
3. Nitinol resitivity, $\rho = 7.6 \times 10^{-5} ohm/cm$.
4. $P = E/t$ (E is energy and t is time in seconds).
5. Latent heat of transformation of approximately $20J/g$ and a specific heat of $0.01J/gC$.

The equation for the Joule heating is $P = I^2R$, where P is power, I is current, and R is resistance. Resistance can be calculated using resistivity: $R = \rho L/A$, where

ρ is resistivity, L is the length of the mechanism, and A is the cross-sectional area. For nitinol, $\rho = 7.6 \times 10^{-5} ohm/cm$. To determine the amount of power that needs to be delivered to the nitinol mechanism, $P = E/t$, where E is energy and t is the time in seconds. Nitinol has a latent heat of transformation of approximately $20J/g$ and specific heat of $0.01J/gC$ [30].

Related Terms

Those related terms are explained in Figure 2.4

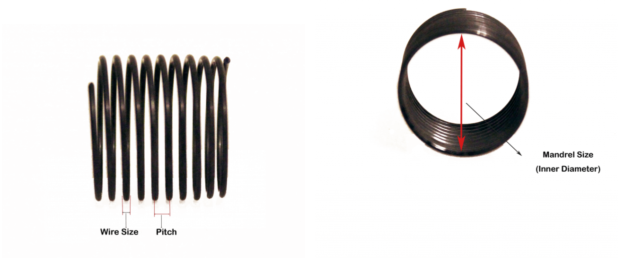


Figure 2.4 Related Terms for Nitinol Micro-Springs [3]

- Wire Diameter
- Inner Diameter
- Pitch
- Turns

SMA Actuators for Haptic Interface

Springlet by Hamdan *et al.* [32] is a very close related work that proposes an expressive interface on the skin. This work uses medical-level tape to fixate the SMA on the skin. The lightweight device creates a directional sensation with the shearing force applied to the skin. Chernyshov *et al.* [33] proposed an SMA-based haptic ring for notification.

Limitations and Reasons to be Chosen

The SMA actuator has an extremely large force-weight ratio, which means for generating the same power, it is lighter. The actuation of the SMA is not linear but more of lifelike movements, which is a good point to be chosen for on-skin actuators.

The heat generated by SMA actuators and thereby, slow actuation remains to be the main issue to be mentioned in the field.

There are some researchers exploring fast and accurate control of SMA actuators using its feature of self-sensing [34]. However, it has not yet been studied by this thesis.

In this thesis, we tried three types of SMA actuators. Two are from Toki Company[2] the Biometal Fiber and the Biometal Helix, and another is the SMA micro-spring actuator from Kelloggs' Research Labs[3]. Also, due to the power and heat issue, we chose the latter one. This will be described in detail in Chapter 3.

Table 2.2 Comparison of Soft Actuators

Actuator	**Actuation Condition**	**System Weight**	**Sensation Feature**
Pneumatic Actuator	Pressure	Bulky with Pumps	Soft and Powerful
Dielectric Actuator	High Voltage (such as $1000V$)	Bulky with the Power	Vibro and Fast
SMA Actuator	Heat or Comparatively High Current (such as $400mA$)	Lightweight	Lifelike and Slow

2 Biometal, Toki Company, https://www.toki.co.jp/biometal/

3 SMA Micro-spring, Kelloggs' Research Labs, https://www.kelloggsresearchlabs.com/product/micro-springs/

2.5. Summary

In this chapter, related work is categorized into different aspects. From the body perspective, we talked about human skin function first and noticed that the importance of the sense of touch and introduce the basic knowledge to understand the haptic sensation at the very essence. As a result, we chose to focus on the large area of the body, which leaves us to FA-II.

Then the previous applications through haptic augmentation are shown, most of them are using vibrotactile sensation most for notification and entertainment because it is a mature, relatively cheap and reliable method. The haptic sensation of vibrotactile type is usually tougher compared to what we propose afterwards.

The second skin idea has been popular both in fashion and research field. In the fashion field, people are more focusing on using the second skin to have social bonding or communication with information data. In the research field, new material has been studied to make a "real" skin. Second skin with different inputs and outputs have popped up. There is a great work from the feel-through tattoo, which is impressive. However, their method is different from this thesis.

Soft actuators and its existent mechanism for haptic augmentation were also discussed. The pneumatic actuators are considered too bulky with the pumps. The dielectric actuators are thought to be not safe enough for haptic sensation, and tough for us to customize. Therefore we chose shape-memory alloys as our actuator with high recommendation of its lightweight feature and good force-to-weight property.

We proposed a developable modular actuator for creating soft programmable haptic sensation based on the shape-memory alloys.

Chapter 3
Skin+

In this chapter, first, the ideation of Skin+ will be introduced, where the concept of Skin+ is included. Then the functional design based on the concept will be discussed along with the prototypes. After that, the design and actuation of modular Skin+ will be described. Last but not least, the implementation of Skin+ will be elaborated.

3.1. Skin+ Ideation

In this section, the inspiration, concept, and the definition of Skin+ will be given.

3.1.1 Background

The evolution of human is fascinating and has been studied by many researchers. Along with the evolution, how the skin has changed and will change inspires us.

What Will the Skin Be like in the Future?

You can imagine that in 2050, you do not need a physical phone to gather information. Human skin itself will be a perfect carrier for the future interface. The way of acquiring the information, instead of sight, haptics will take a growing position. The skin, this large organ will be emphasized with its function. A lot of animation and fiction novels have pictured the future such as "ghost in shell" which describes the artificial body. The skin will serve as a growing functional and crucial role in people's daily life. The skin function this thesis looks into is the sense of touch, the ability to communicate with the outside world.

Sense of Touch Has Its Limitations.

The sense of touch is regarded as one of the oldest perception human would develop when they were born. We can perceive the outside environment through the touch. However, it has physical restrictions. We cannot touch things out of our reach as shown in Figure 3.1(left) Skin+ is aiming to feel beyond these physical constraints. With Skin+ we focus on reproducing the haptic sensation on the skin to let users feel the object through the skin at a distance as shown in Figure 3.1(right). .

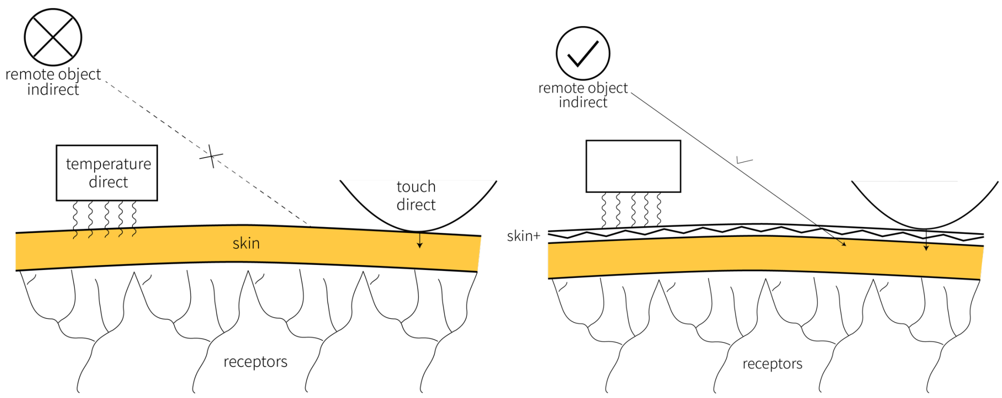


Figure 3.1 Proposed Concept of Interface with Skin+

This is where this project Skin+ started.

3.1.2 Insights

Based on the previous key idea of perceiving distant objects on the skin, we look more into the forms correlated to the idea we would like to present.

"Noise" in Haptics: Friction

If you slightly move and carefully feel your body, the sensation of clothes moving on the skin might be felt. This kind of sensation happens every day, every hour, every minute, and even every second. It is like noise in a haptic sense. Therefore, our body tends to "ignore" those sensations or get used to them. However, this kind of sensation can be useful and non-obtrusive if we manage to arrange them smartly. Therefore, we decided the type of haptic sensation we want to go with is a new friction sensation inspired by this trivial phenomena.

Lifelike Movement: Breathing

Like the goosebumps on the skin, we want the sensation to have a coherent behaviour and make sense to some extent. What comes into our mind is the creature's breathing behaviour. Breathing is the process of moving air into and out of the lungs to help gas exchange with the internal environment. In the process of breathing, our body, to be specific, the ribcage will increase its anteroposterior diameter when we inhale the air. The breathing can be categorized into several styles based on the frequency. We may puff and pant when we breathe too frequently, which may also show the tense. It is also not uncommon that we take a big, slow breath to calm down ourselves. The breathing behaviour would be a good metaphor for the chosen movement we would like to use in this thesis.

Flexible Structure: Auxetic behaviour

The auxetic structure is a perfect option for expanding and closing movement. First, we will explain the meaning of auxetics. Note that we only talk about 2D auxetic structure in this thesis.

Usually, things obtain a positive poison ratio. So, when you compress on the one sides, the other sides will expand. Auxetics or negative poison ratio means when you compressed on the one sides, the other sides will contract. Grima and Evans found auxetic behaviour in the rotation of connected squares [35]. The rotating units will show auxetic behaviour. Therefore, we chose a simple triangle for creating an auxetic structure.

3.1.3 Concept

Inspired by what mentioned above, *Skin+* (Skinplus), an organ extension has been proposed. Based on the idea of "a transparent on-skin haptic channel for future skin", several decisions have been made to focus on the core concept of the thesis: Determine that

1. type of haptic sensation is friction sensation;

2. linkage mechanical structure is used to generate the haptic sensation;
3. technology to apply in this system is shape-memory alloys.

The definition of Skin+ is explained in two levels:

- Concept: Skin+ is a new organ extension to expand perception without contact.
- System: Skin+ is a modular on-skin haptic device for haptic augmentation.

Skin+ serves as a modular, expressive, lightweight on-skin system for haptic augmentation, which contains a vivid movement of breathing, crawling, pinching, tapping and slipping relative onto the skin to create a novel haptic sensation.

3.2. Functional Design

The haptic sensation delivered by Skin+ is from the motion of the modules. The mechanism which contains vivid movement is fulfilled by a designed structure inspired by the auxetic structure. The structure will provide a friction sensation for a certain area of the skin, providing a new type of friction sensation. For clarifying the core purpose, a simple auxetic structure has been decided and applied at the early stage in the research. Hand prototypes, sleeve prototypes have been conducted for preliminary study on the function design for the Skin+. Also, then the motion study and the module tests have been run for the modular prototype. The final functional design has been established.

3.2.1 Core Mechanism

SMA Actuator + Mechanical Structure

The SMA actuators have been carefully chosen to enable the control for the actuation for friction sensation on the skin. The pros and cons of SMA actuators have also been described in Chapter 2 in detail. We apply current to control the SMA actuator in this thesis. The setting of the SMA actuators has changed during the process of the Skin+ study to reach a better control for the physical structure, also because of the usage of different types of the SMA actuators. We utilize the contraction and expansion to control the mechanical structure. Without any use of heavy servos, this mechanism is lightweight, silent, and expressive for actuating the mechanical structure. In this thesis we started from studying the auxetic structure then we further divided the structure into the fundamental single linkage to study the behaviour of the structure combined with the actuator.

3.2.2 Hand Prototype

A preliminary prototype of the proposed interface has been first implemented, as shown in Figure 3.4. An auxetic physical structure and a shape-memory alloy dual-wire actuator make up this prototype. Actuated by a microcontroller, the wire leads to contracting or releasing the shape of the cells.

Figure 3.2 Hand Prototype

1. Auxetic Structure

   The 2D auxetic structure presents negative Poisson's ratio behaviour. When being pressured from the sides, it contracts in all directions in parallel to the surface. The 2D re-entrant structure shows the auxetic behaviour. The structure has been chosen and iterated the tips for a better sensation.

2. SMA Actuator

For SMA, BioMetal Fiber (BMF)[1] is used to actuate the whole auxetic structure cells. This wire is responsive to the applied current by contracting. If the applied current rises above a specific threshold (600mA in this case), the SMA wire will contract by a certain percentage of its length (4%); and if the current falls under the threshold (around 200mA), the wire will return to its original length. The SMA is a typical two-way type. Two-way means the SMA will remember two shapes both in high-temperature and low-temperature conditions.

3. Configuration

   The prototype is made of three layers: the cover layer with a 0.5mm thick white fabric, the actuation layer with a $0.2mm$ transparent foldable Polyethylene terephthalate (PET) sheet and the protection layer with a $0.3mm$ transparent silicone sheet (Figure 3.3(c)). The shape of the center of the cell went through a series of design iterations and enabled the cell to provide the sensation of pinching. All the layer were laser cut, as the easiest and fastest way to prototype such a device. As for the actuator, the BMF150 (diameter $0.15mm$) is twisted in a double-wire to increase the contraction force. The prototype is adjustable to fit various hand sizes.

4. Motion Design

   A three-cell prototype was implemented that each cell contains one BMF wire to control its behaviour (Figure 3.3(a)). On the one hand, they are controlled separately through different channels. On the other hand, when one cell is actuated, the physical connection between cells will pull over other cells to let friction provide haptic sensation.

5. Implementation and Evaluation

   In this preliminary work, *Skin+*, the prototype was tested on the user's hand easy for calibrating the amount of driven current to the threshold of haptic sensation. In the tests, the maximum actuation current is around $570mA$. When the temperature reaches $67°C$, the shrinking process finishes. When

1 Model number: BMF150 by Toki corp, Japan

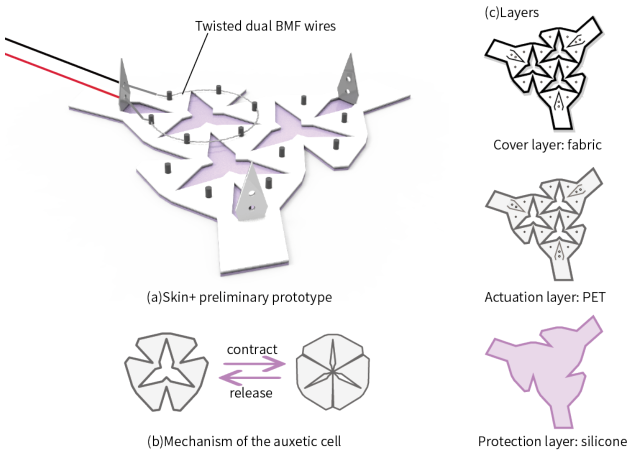


Figure 3.3 Configuration of Hand Prototype

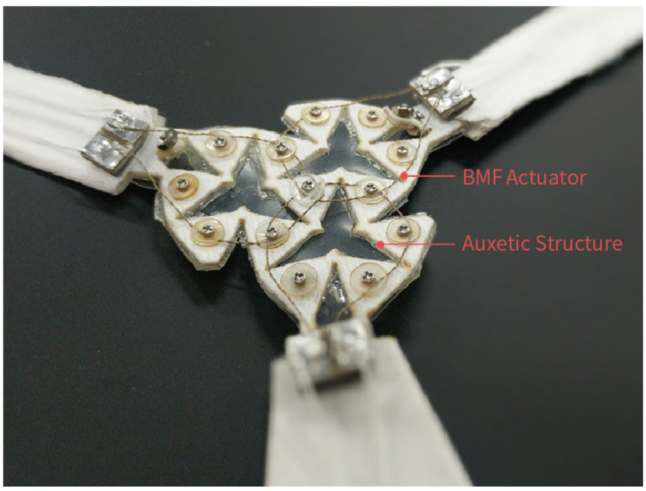


Figure 3.4 Implementation of Hand Prototype

it falls on $27°C$, the releasing process finishes. Two parallel evaluations were conducted. One was conducted in the virtual reality environment without head-mounted display. The key task of this evaluation is to let users feel the virtual wall, so the Skin+ prototype was worn on the back of the hand. The application for the evaluation is applied in the Unity software [2]. The input of this application lies in the distance between the module on the hand and the virtual wall. The hand posture is detected by Leap Motion [3]. Moreover, a virtual module is created in the Unity based on the real position of Skin+ hand prototype. The other was conducted in the Processing software [4]. The key task is to hit the virtual ball on the ground. Therefore the Skin+ prototype was worn on the palm.

Figure 3.5 User Test for Hand Prototype

6. User Feedback and Reflections

   This preliminary prototype was tested with three participants (Figure 3.5). The limitations and discussions for the preliminary prototype are as follows: Users commented that the haptic sensation was felt in representation of an

2 Unity, https://unity.com/

3 Leap-motion, https://www.leapmotion.com/

4 Processing, https://www.processing.org/

area (P1, P3). It felt soft but got too warm very soon (P2). In short, one main consideration faced during the preliminary tests is the overheating of the BMF when actuated. Besides, the contracting of the structure is so small that users tend to ignore it and confuse the sensation with heat.

3.2.3 Sleeve Prototype

In the next prototype, in order to fabricate a less rigid and heat-proof physical structure, with the top and bottom material replaced, the sleeve prototype was made.

1. Generative Model

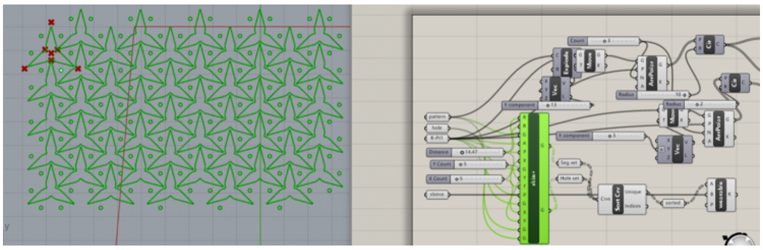


Figure 3.6 Generative Prototyping

As mentioned above, the auxetic structure can be made from a concave rotary cell. Therefore, for fast prototyping, we design a generative model in Grasshopper, a plugin for the 3D modelling software Rhinoceros [5]. We set several parameters, such as the number of rotate points, and the distance between the center point to the outward point to determine a single cell. We want to use the model to leave its capability of exploration and customization.

2. Configuration

From top to bottom, the cover layer is GORE-TEX fabric, actuation layer is the same 0.2mm foldable PET sheet, and the protection layer is a 4-way

5 Rhinoceros, https://www.rhino3d.com/

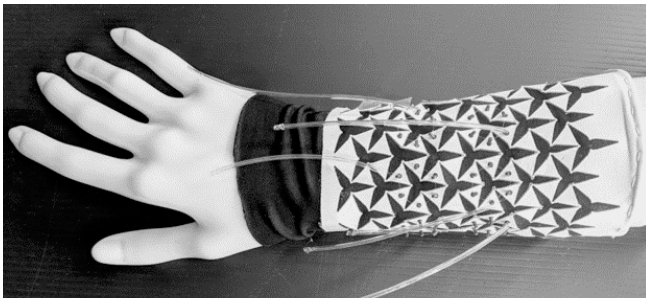


Figure 3.7 Sleeve Prototype

black fabric with 3D-printed pin which enables wires to go through instead of threading under the washer for a better force balance.

3. Circuit Fabrication

   In the previous prototype, the circuit was implemented on the breadboard. In the sleeve prototype, we updated the circuit set-up. A shield PCB board compatible with Arduino Uno [6]with six channels to control the cells was designed in the software Diptrace and fabricated as shown in Figure 3.8 [7]. One single MOSFET is used to control one channel and allows enough current to go through when actuated. The set-up of one channel is made up of one 2SK4017 Mosfet to work as a switch, one 1K ohms resistor to protect the current going through Arduino and one 10k ohms resistor from gate to the ground.

4. User Tests and Reflections

   This prototype was tested only with actuation output without application scenarios. The black fabric solves the main heat issue, but still, the movement is not clear enough, and when people tried it on, they can barely feel it because of the actuator on the 4-way is way too light compared to the 4-way fabric itself.

6 Arduino, https://www.arduino.cc/

7 Diptrace, https://diptrace.com

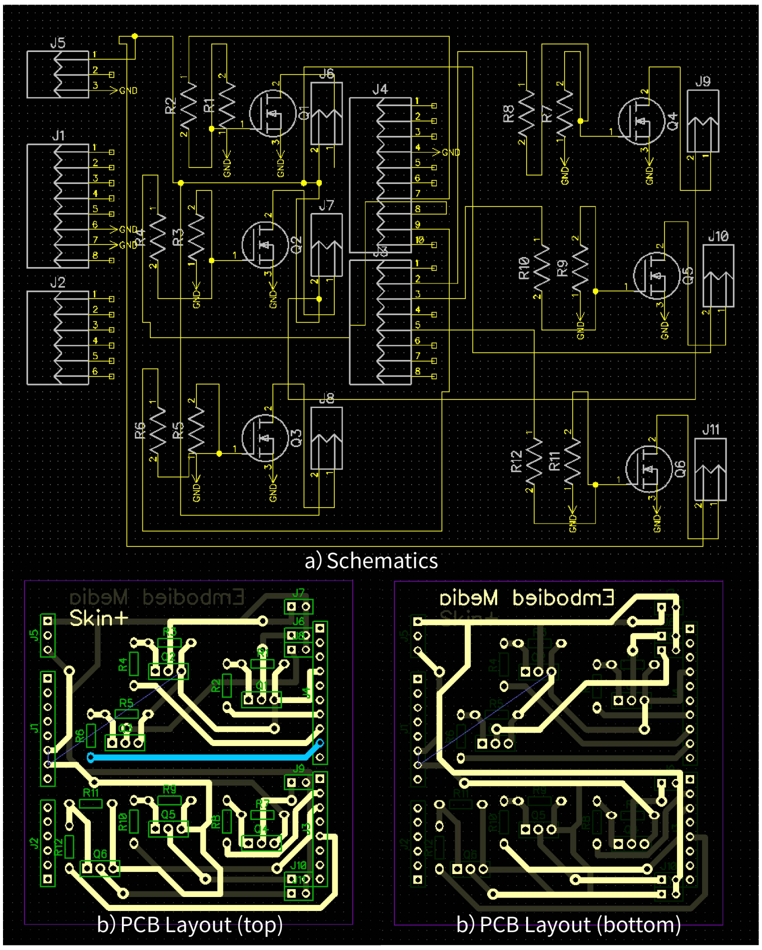


Figure 3.8 Schematics and PCB Layout in Diptrace

The two preliminary prototypes give great insights to the next stage. Due to a high and detailed requirement for the linkage in the auxetic structure, instead of using the material properties to move, we implemented a modular prototype as our preference. For the actuator side, although the BioMetal series of SMA actuators have good properties as an SMA actuator, it is not suitable for Skin+ case mainly because of its high-temperature consumption. Therefore we finally chose one-way SMA actuators to replace the one we used before.

3.2.4 Modular Prototype

Based on the knowledge and insights we gained from the preliminary prototypes, Skin+ was then implemented in a modular type. The modular Skin+ consists of the modular 3D-printed physical auxetic structure and the one-way shape-memory alloy micro-spring actuator from KRL[8] [3].

Motion Study

To have an intuitive and thorough understanding of the movements of our modular structure, we combined three methods to analyze the motion of Skin+.

- **Physical Modules**

  We first made a physical prototype (Figure 3.9) in the software Fusion360 [9] to test the movement of a large area of modules connected. As the image shows, the large area of the Skin+ modules has a largely dependent expansion and contraction.

- **Simulation**

  Then, we conducted a simulation of motion study on single and multiple cells in the software Fusion360 to see the angle the single unit rotates and distance it moves as Figure 3.10 shows.

- **Mathematical Model**

8 Model number: 5-NiTi-0.25-0.5 Nitinol Micro-Springs by Kellogg's Research Labs, USA

9 Fusion360, https://www.autodesk.com/products/fusion-360.com

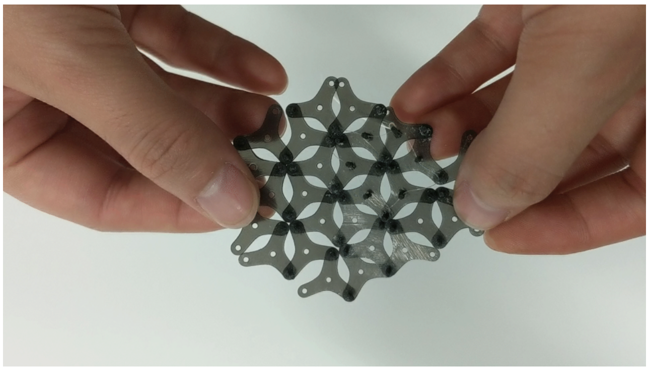


Figure 3.9 Physical Model for Motion Study

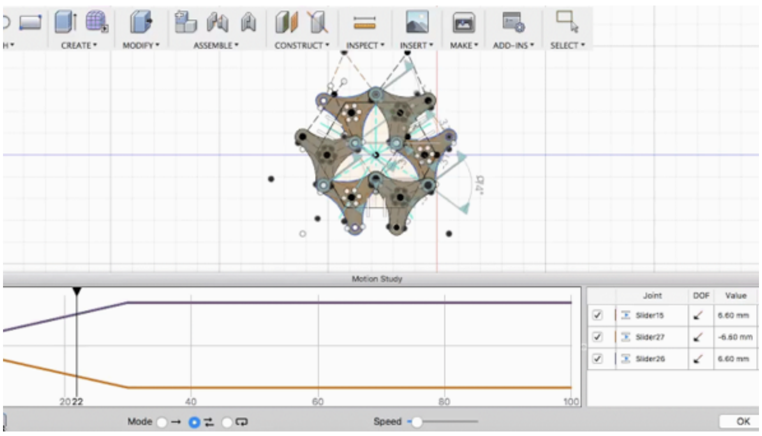


Figure 3.10 Motion Study in Fusion360

To measure the movement carefully, we created a mathematical model for Skin+. The parameters we use are shown in Figure 3.11.

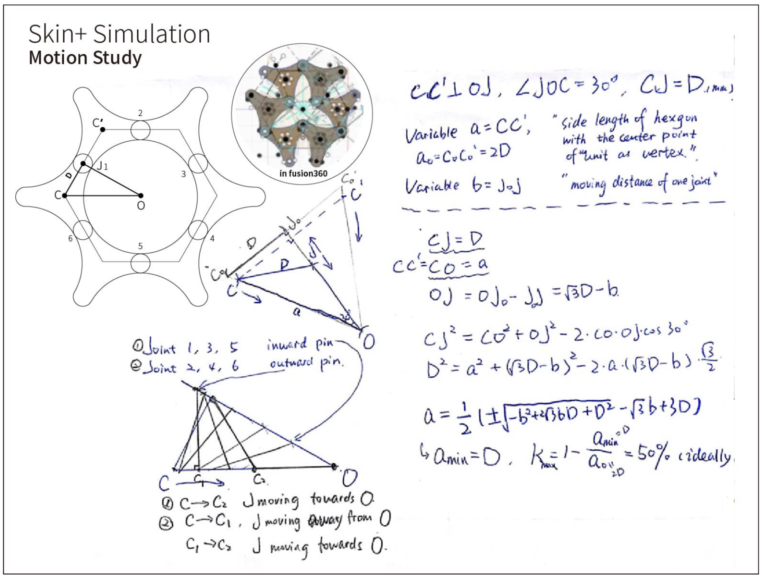


Figure 3.11 Mathematical Model

Choosing SMA Actuators

The difference between one-way and two-way SMA actuators are shown in Figure 3.12.

For the first actuator we tried, a two-way SMA Biometal Fiber, it has a small force and small displacement (about 4%) and high transition temperature (about $70°C$). Therefore although we make it dual but still the displacement is not enough. Then we tried one-way SMA Biometal Helix, it has even smaller force than Biometal Fiber but large displacement around 50%. It has the same high transition temperature (about $70°C$).

To prototype our modular skin+, we changed our SMA actuators from 0.15mm diameter Biometal wires to SMA micro-spirng with a 0.25mm diameter to have larger force with a lower transition temperature at $45°C$. It has a large force, large displacement and low transition temperature with a little trade-off on actuation

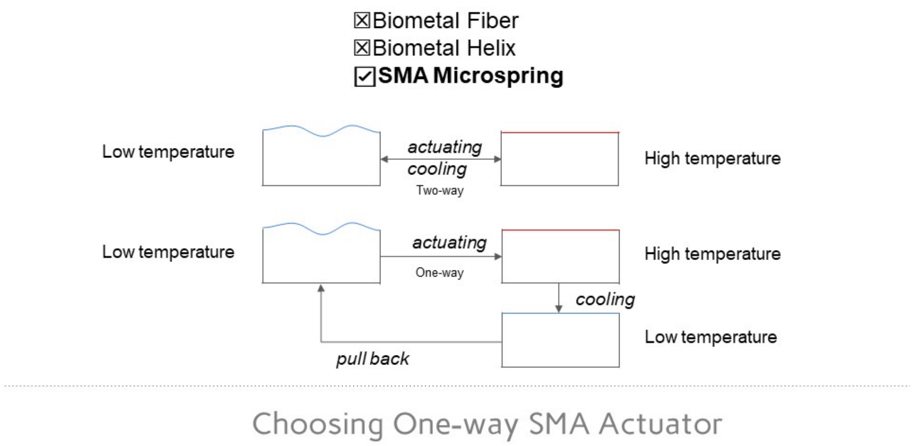


Figure 3.12 Mechanism of One-way and Two-way SMA Actuators

speed. Therefore we chose this SMA actuator. You can actuate the SMA microspring through the current, and it will contract when it reaches the temperature ($45°C$). When you stop applying current to it. It will not come back to the position it originally was. But the crystal will change to be flexible for us to pull it easily.

Configurations

The final module is designed in the software Rhinoceros (Figure 3.13). The size of one cell module is $45mm \times 40mm \times 1mm$. A washer is created for tightening the marginal pin. The units are categorized into four types ("F" stands for female, and "M" stands for male): "FFF", "FFM", "MMF" and "MMM". Note that in this specific prototype, we only used MMM and FFM to construct. The male pin has a small snap joint to go with the cap. Due to the quality of the print, the snap joint cannot be effective as expected.

- **Linkage**

  The design of the module has been a long process because of the requirement for the linkage. We went through three main design stages for the pin of the module.

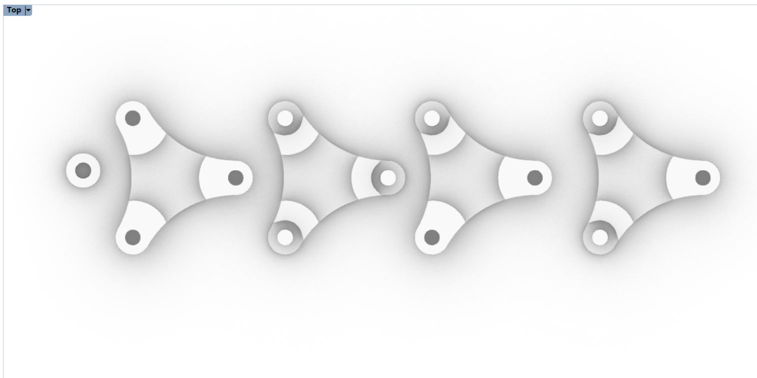


Figure 3.13 3D Modelling for Modular Prototype in Rhinoceros

1. “F” = Hole, Independent pins

   First, We utilized two “F” s with an independent pin to create a single linkage. The holes were set in three directions with different height. However, the pin itself was not stable enough, and there were too many parts moving at that single point so that the motion of the units made the pin sloping.

2. “F” = Hole and “M” = Long pin with holes

   Secondly, we combined the independent pin with one “F” to make an “M”. So it was one “F” and one “M”. It turned out when we applied the SMA actuator on the units; it was not moving in a flat surface but moving up or down. The mechanism for combining two one-way SMA actuators would not be suitable for this. Also, it would be peeled off sometimes when we wore it on the skin. Because there was no stopper on the top.

3. “F” = Shell with holes and “M” = Short pin

   Then, we changed the female pin to be a shell with holes and shorten the male pin. It solved the peel-off problem. However, it did not solve the other problem. It elongated the distance for the leverage of moving up or down.

4. “F” = Hole, “M” = Short pin, Caps

   After that, we changed the female pin back to the hole, kept the male pin short and added caps as a fastener for the linkage. The limited contact space in the linkage made the model move not ideally in a flat surface.

5. "F" = Long Hole, "M" = Medium pin, Washer

   In the end, we changed the female pin back to the hole, but a long hole. We made the male pin slightly longer and added washer as a fastener for the linkage. The contact area for linkage is a cylinder contact which is more reliable than before. Also, the model become tougher because we modified to make a larger joint (we added the height) (Figure 3.14).

Figure 3.14 3D Printed Modular Prototypes

- **Thickness**

  Based on the core principle of the Skin+, we want the thickness of the module can be as thin as possible. In the early fabrication period, the thickness of the module has been tested with $0.4mm$, $0.8mm$, $1.0mm$ and $1.2mm$. The $1mm$ was chosen as an appropriate thickness for the module based on its rigidity and possibility to be slightly bent when applying on the skin.

- **Angle**

  The angle of the unit rotating will determine how much movement the module have. Because of the actuation method, theoretically, the angle of the module has been sent to $-30°$ to $+30°$. However, in the real world, we also have to consider the width of the pin. As shown in Figure 3.2.4, we calculate the maximum angle, which is approximately from $-15°$ to $+15°$. We made a small stopper on the linkage to restrict the cell moves within the desired angle.

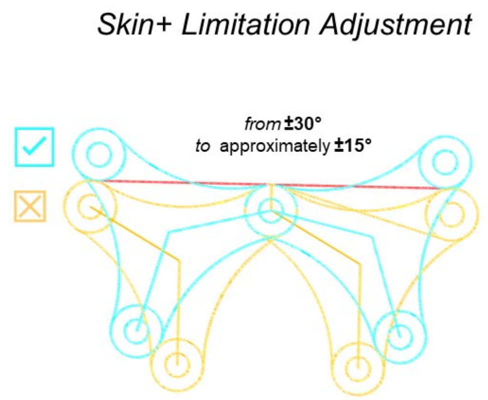


Figure 3.15 Modelling and Calculating Angles for Stoppers in Rhinoceros

- **Material**

  The module was printed in Formlabs Form2 printer using the regular resin due to its capability to bear high temperature ($200°C$) as shown in Figure 3.2.4. Previous modules were done in Object260 using material VecroBlack. It turned out the material was not tough enough and cannot bear the required temperature so that we chose the resin printer for our final prototype.

- **Pivot Point**

  We doubled the layer for our model in our prototyping because of the force functioning point. Although in the previous version, we set the point as low as possible, it still turned out pulling the cap out of the pin from time to time. So we re-considered this problem and set a double layer to make the pivot point in the middle of the module to give force balance. However, it doesn't work out as we wished. The doubled model seemed to be too stiff for our skin concept and more likely to become a device instead. So we finally chose back the single layer to give good flexibility and have more fitted our theme. We added cylinder contact in the linkage and tightened the pin to overcome the problem.

Figure 3.16 Prototyping with Formlabs Form2 Printer

- **Base Material**

  For the wearability, we added another layer under the modules. Inspired by the previous sleeve prototype, we utilize a 4-way Polyester-Nylon Fabric to serve as the base material. It is the direct contact to the skin where the friction sensation happens.

- **Mechanism**

  The mechanism for one-way SMA actuators is to combine two one-way SMA actuators to create a two-way effect to enable the structure to be responsive to the applied current. The transition temperature for this type of SMA is $45°C$, which is safe to the skin. To present the two-way effect, we considered two actuation methods along with the circuit design as the image shows.

  1. "Parallel"

     A single actuation structure will contain two joint units with SMA actuators connected on the inside and the outside. The actuators opposite to each other will not be actuated in the meantime.

  2. "Serial"

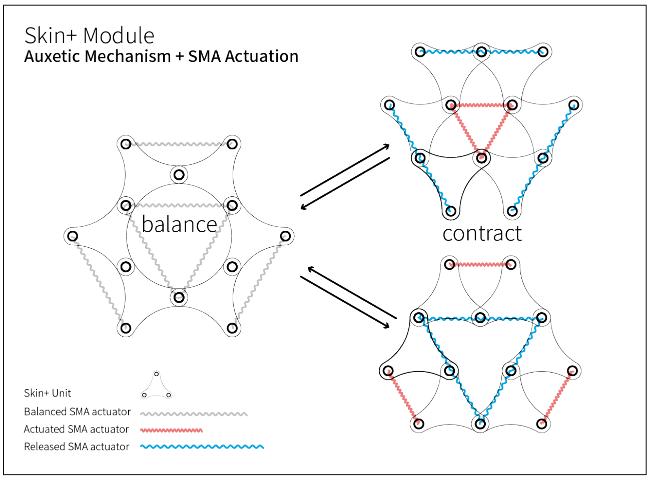


Figure 3.17 “Parallel” Mechanism

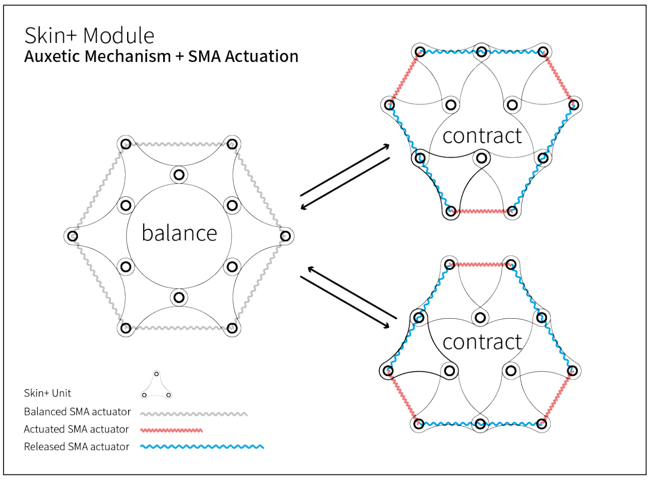


Figure 3.18 “Serial” Mechanism

A single actuation structure will contain the whole cell with SMA actuators connected on the outside. The actuators next to each other will not be actuated in the meantime.

The "Serial" mechanism has been chosen at first because of its relative simplicity. However, through the test, we learned that it is not a good mechanism to set up the SMA as "Serial". We went through several failure tests to learn that lesson as shown in Figure 3.2.4.

The "Parallel" mechanism has been chosen in the end. The basic mechanism works with two modules. Therefore, it can be divided into a single two-module pair for proof of concept, which enables the evaluation process smoothly. Also, the outside is not a good place to set all SMA actuators because for the whole structure the pivot point is in the center of the structure, which adds the length for the lever resulting in easy to be flipped.

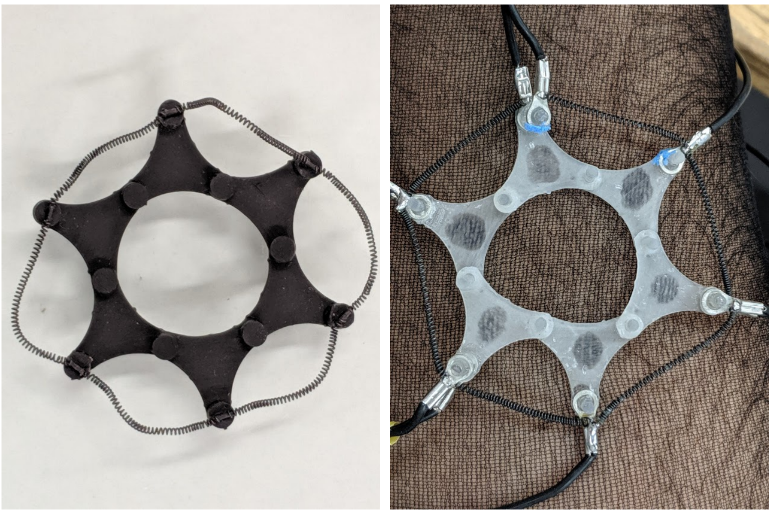


Figure 3.19 Failure Test in "Serial" Mechanism

- **Actuation Circuit**

  For the circuit, for one-way actuators, we considered in two ways:

  1. Using Diodes and Motor Drivers

Based on the repellency of the neighbouring SMA actuators, we used diodes to guide the direction of the current and the motor driver to alter the direction and enable high current. A motor drive board along with diode sets have been used to manage and alter the direction of the current.

2. Using Mosfet

   The Mosfets with resistors groups as the previous setting are still the best suitable choice for this project, which makes things clearer and simple. So we used Mosfets in the end.

- **Actuator Test**

  SMA micro-spring actuator's features are as follows

  1. Transition temperature: $45°C$
  2. Wire diameter: $0.25mm$
  3. Inner diameter: $0.5mm$
  4. Pitch: One wire size (tight) to four wire size
  5. Length: $12mm$
  6. Turns: 48
  7. Resistance (in room temperature): around $2.2ohms$
  8. *Special feature: SMA micro-spring has been ordered passivated for connection without deteriorating the shape memory effects.

  The selection of the actuating channel drives Skin+'s actuation, the amount of the current and the delay time which controlled by the microcontroller. A baseline study of a one-way SMA actuator, the SMA micro-springs was run to understand the SMA actuator's actuation condition with the PWM output using Arduino. One single SMA actuator is tested as shown in Figure 3.20. We got the reference of control time and applied current.

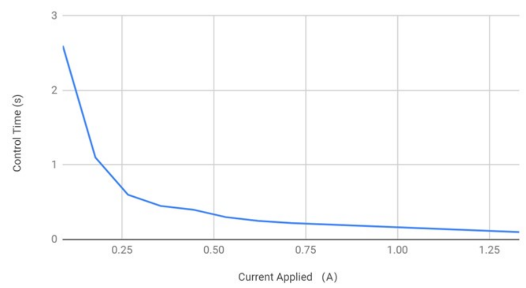


Figure 3.20 Test on Single One-way SMA

3.3. Modular Skin+

In this section, the design and implemented hardware and software of the Skin+ system will be introduced.

3.3.1 Modular Design

Let us introduce the modular Skin+. As shown in Figure 3.3.1, one unit is a Skin+ Atom. With one atom, it cannot give any movement. The smallest feasible part is the two atoms which create a Skin+ bond. It has a two-way movement. Then we can also use three atoms to create an open chain to have a larger functioning distance or four atoms to create a closed chain to have rapid vibrotactile sensation. With six atoms we have our familiar Skin+ Auxetics.

3.3.2 Configuration

Inspired by the previous sleeve prototype, we put 4-way fabric under it to let users wear it easily. We use laser-cut to locate the position for Skin+ bonds to be put on the position. We made a fabric-based modular prototype with antagonistic pairs of SMA actuators.

As shown in Figure 3.3.2, we implemented a front cell, Skin+ Auxetics and a side array Skin+ Array on the prototype. A five-bond skin+ prototype was

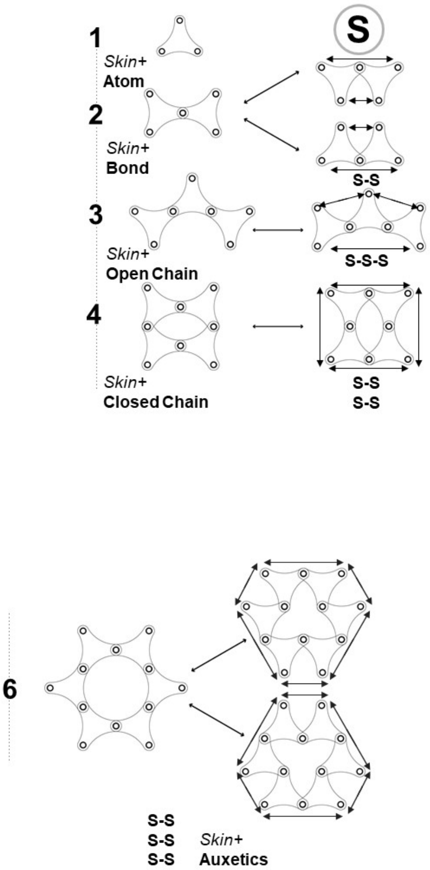


Figure 3.21 Concept of Modular Skin+

fabricated for the evaluation. The neighbouring one-way SMA actuators are controlled through independent PWM channels. We use esp32 microcontroller which is controlled via Bluetooth from Unity.

Figure 3.22 Fabric-based Modular Prototype of Skin+

Hardware

The is the circuit overview in Figure 3.3.2. Skin+ Array consists of 5 Skin+ bonds, 10 channels. Skin+ Auxetics is made up of 3 Skin+ bonds, it has 2 channels.

The hardware of Skin+ system shown in Figure 3.3.2 contains Skin+ physical module (units and washers), SMA actuators (10 SMA micro-springs for Skin+ Array and 6 SMA micro-springs for Skin+ Auxetics), Esp32, shield PCB board (Mosfet and resistors) and the batteries. Note that the input is not included or designed in this system.

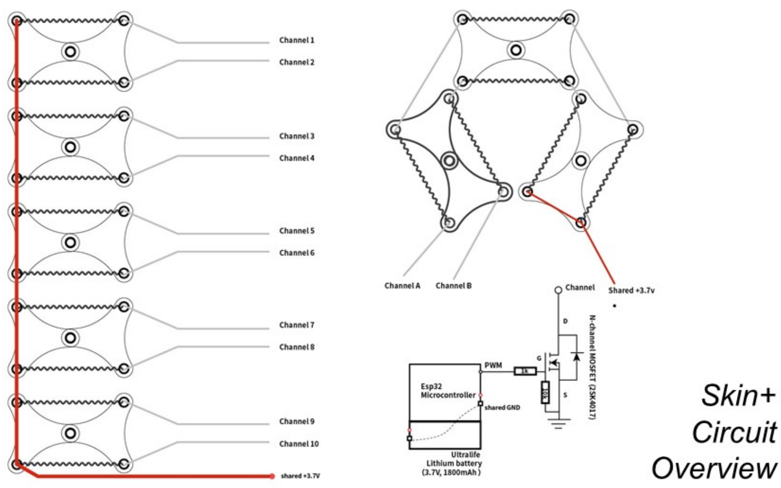


Figure 3.23 Circuit Overview of Modular Skin+

Software

The software Skin+ system used mainly consists of the Unity and Arduino platform. The data is sent from Unity to the Esp32 to form an open-loop control. The control curve can be modified over the curve tool in Unity as shown in Figure 3.3.2. We did pretests and implemented two control curves for Skin+ Auxetics (Figure 3.3.2). One is actuating forward and going back; the other is actuating forward, actuating back and returning to the original position. We implemented a simple square curve for open-loop control for Skin+ Array in the evaluation.

3.3.3 Applications

The main function for Skin+ is to expand or alter the perception. It can be used in daily scenarios as well as VR environments.

Collision Avoidance

When we are occupied by phones, we tend to be unaware of the surrounding. Skin+ is considered to be able to support a similar situation. Through setting up Skin+ modules onto different body sites to form a collision avoidance system.

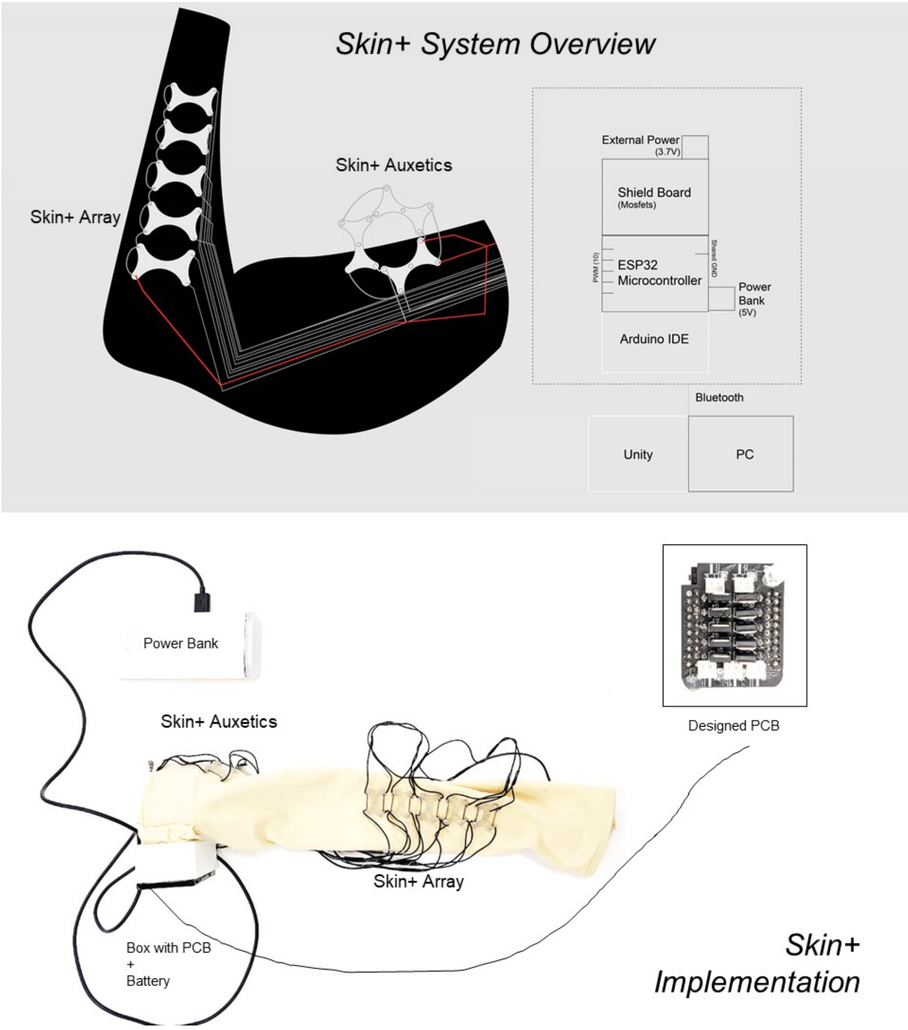


Figure 3.24 System Overview of Modular Skin+

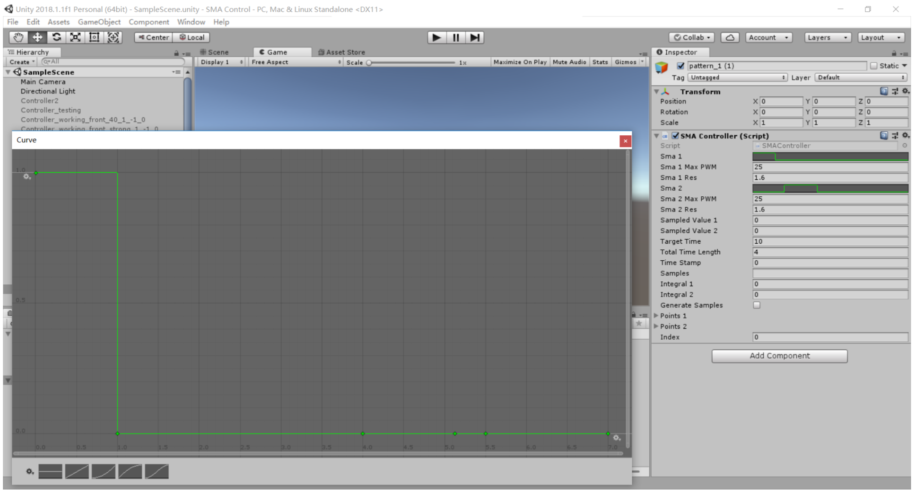


Figure 3.25 Open-loop Control in Unity

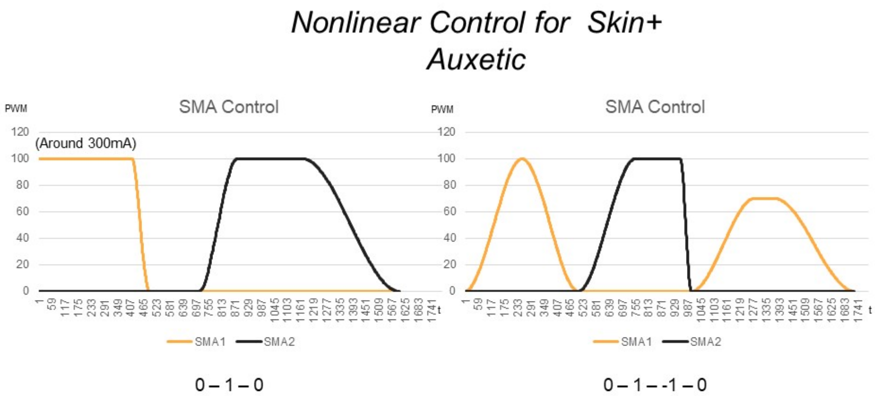


Figure 3.26 Nonlinear Control of Skin+ Auxetics

VR

Another application is in VR environments. When people are in VR environments they can feel the environment through Skin+ modules and also as an expressive display for the audience who are around them.

3.4. Summary

In this chapter, at the very beginning, we introduced our concept of Skin+. Many aspects have inspired Skin+. People ignore the friction sensation happening every second on their body and consider it is noise that can be ignored. The breathing behaviour with a simple opening and closing movement has deep meaning because of the rhythm. That is another inspiration. The aesthetic and functional structure auxetics contributes to this work a lot. Then the functional design was talked. The combination of Shape memory alloys and the mechanical structure is one key mechanism what we used in this thesis. Then we continued to describe the functional design along with our different prototypes at the early stage. We got user feedback from each stage, reflects and improves and therefore, Skin+ is also evolving through these two years. The finalization of our Skin+ module was introduced. The design of Skin+ module was difficult, time-consuming but worth doing. Through the design, we were able to deeply understand the motion of the structure, which was also the key to the desired haptic sensation. Our whole system is focusing more on the output end so that the input is not included in this thesis. In the next chapter, We will describe our evaluation from different perspectives.

Chapter 4
Evaluation

In this chapter, to evaluate the functionality and usability of Skin+ as an on-skin wearable haptic interface, four core questions coming up are whether:

1. Skin+ can give soft actuation on the skin;
2. Users can differentiate the position and the intensity of the stimuli on Skin+;
3. Users can recognize the patterns of the stimuli on Skin+;
4. Users think they feel augmented using Skin+.

To answer these four questions, the evaluation was done from three perspectives. One pretest, one psychophysical study and one user study for validation in the daily scenario were conducted.

The two-point orientation discrimination threshold of the skin was referred from prior works [36] and tried in a pretest. In the psychophysical study, the parameter was measured based on single Skin+ cell. In the user study, proof of concept for Skin+ was evaluated. After that, based on the results, the summary and the limitation of Skin+ will be discussed.

4.1. Pretest

The key points we want to focus on in the pretest is:

What are the minimum and maximum current for the Skin+ system? (I_{max}, I_{min})

A pretest was run to understand the SMA actuator's actuation condition with the power supply. SMA actuators are tested with one Skin+ bond 4.1. We fed the current from 0 and gradually up. There was no visible change before the current was 140mA. The SMA actuator cannot bear the current up to 600mA. Around 400mA is assumed to be a good actuation time for the SMA actuator. When the SMA actuator goes to 400mA, the power supply has a strange behaviour of current fluctuation. The reason was that the SMA actuator has transformation from martensite to austenite, which at that moment a resistance change would happen. Based on the pretest, we set the range of the applied current to the SMA actuator from 100mA to 500mA.

Figure 4.1 Pretest for Skin+ Bond

4.2. Psychophysical Study

In this section, we conducted an absolute detection threshold study and a discrimination threshold study to investigate how users perceive stimuli locomotion on the skin as shown in Figure 4.2, provided by Skin+. Then we gave a questionnaire to survey users' subjective ratings of comfort with the friction sensation based on current and time difference. After that, we decided the magnitude of a set of current and time for the user tests.

Figure 4.2 Participants in Psychophysical Study

4.2.1 Absolute Detection Threshold (ADT)

A staircase procedure will be conducted to decide the minimum current consumed by Skin+, which users can perceive. We want to conduct a standard two-down, one-up staircase procedure for the study.

Participants

6 participants (3 females and 3 males, aged from 23 to 27, mean age = 24.8) were recruited from our institution. The participants signed the contract form and were informed of the procedure of the experiment before the experiment started. None of them reported any health condition that could have affected their performance in this experiment.

Method

A Skin+ module with its actuation system is selected for the ADT study. A single module is around $45mm \times 40mmm$ with $1mm$ layer thickness. The module is worn on the upper arm with Skin+ Auxetics and forearm with Skin+ Array.

The experiment is set to begin with a high-current (500mA), set-control-time(2.5s) stimulus, which is easy to detect. Then the stimulus is reduced until the users show mistakes, where the staircase goes up and then time and the current is increased until the user answers correctly, entering another reversal.

Note that the method used to reduce the stimulus is to set one control time and try the current ranging from 500mA to 100mA based on the baseline study and pretest we have done. The experiment was repeated twice for reliability.

The step for the current in the experiment is 45mA. The actuation time for a certain percentage of contraction is related to the applied current. When participants perceive the stimuli twice consecutively, the applied current would be decreased by a step size. Otherwise, it will increase the step size having a reversal. The participant will directly speak to the experimenter whether they feel the stimulus or not. A new trial starts some randomized seconds after they give feedback to the previous stimulus and reply they are ready. The participants wear the noise-cancelling headphone and being asked not to look at the prototype during the entire experiment. The experiment approximately takes 30 minutes for each participant to complete.

Results

Figure 4.2.1 demonstrates the absolute thresholds averaged over one Skin+ Array and Skin+ Auxetics for each participant. For Skin+ Array, it ranges from 129mA to 157mA. For Skin+ Auxetics, it ranges from 0.176mA to 0.216mA. We defined the appropriate actuation range based on that. As Figure 4.2.1 shows, the red line shows the maximum stimulation intensity (500mA) supported by the Skin+ hardware itself. The highest absolute threshold detected is still far below this maximum. Therefore, the results prove that Skin+ modules successfully deliver haptic sensation on the skin and our hardware's set-up has the capability of reaching the required stimulation intensities.

4.2.2 Difference Threshold (JND)

We also want to see how users can distinguish between the Skin+ stimuli. Therefore we want to conduct a just-noticeable difference (JND) study using the method of constant stimuli.

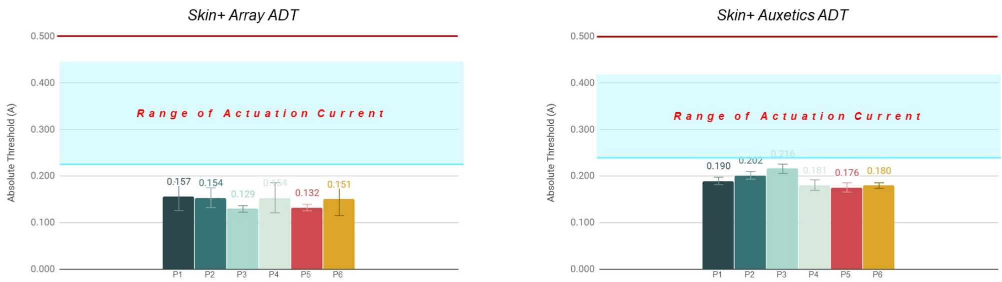


Figure 4.3 ADT for Skin+ Array and Skin+ Auxetics

Participants

The same group of people participated in the experiment. 6 participants (3 females and 3 males, aged from 23 to 27, mean age = 24.8) were recruited from our institution. The participants signed the contract form and were informed of the procedure of the experiment before the experiment started. None of them reported any health condition that could have affected their performance in this experiment.

Method

Each participant needs to answer the same or different for each stimulus pair, which consists of a baseload and an offset load value. The unit in Skin+ module can only rotate from -15 degrees to 15 degrees and must rotate some degrees from their neutral state to reach the minimum detectable threshold.

Therefore, the range is restricted to some degrees based on ADT results from the neutral state of the Skin+ module. The base current and offset current is set different for Skin+ Array and Skin+ Auxetics. The order of trials is randomized and counterbalanced. Participant must repeat two reversals. The interval between the stimuli is randomized ranging from 0.5s to 5s. The same group who takes ADT study will be invited to the JNT study with a rest longer than 10 minutes.

Results

The result is shown in Figure 4.2.2.

We define the JND as the power difference where 70% users were capable of

Skin+ Array JND

ΔCurrent (A)	0.271	0.361
0	33.33%	16.67%
0.045	83.33%	33.33%
0.090	83.33%	66.67%

Base Stimuli Current (A)

Table: **Percentage of Responses that Judged the Two Stimuli as Different**

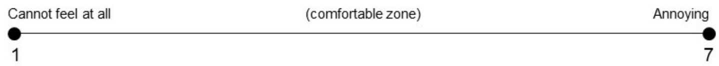
Skin+ Auxetics JND

ΔCurrent (A)	0.241	0.301
0	16.67%	16.67%
0.03	33.33%	33.33%
0.06	100%	83.33%

Base Stimuli Current (A)

Table: **Percentage of Responses that Judged the Two Stimuli as Different**

Figure 4.4 JND for Skin+ Array and Skin+ Auxetics distinguishing. For the 30% error level, we knew that the difference where we can assert the assumption of participants only confusing two different kinds of stimulus in 30% of instances.



	Array (PWM)	Rating	Auxetic (PWM)	Rating
P1	40	5	110	4
P2	40	3	100	3
P3	40	4	125	3
P4	30	4	110	4
P5	40	4	130	3
P6	50	4	120	4
Average(PWM)	40	4	116	4
Average (A)	0.361		0.349	

Rating for Actuation

Figure 4.5 Actuation Rating for Skin+ Array and Skin+ Auxetics

Skin+ Auxetics did not give clear feedback to the users based on the interview we had, so we didn't use it in the user tests. Too strong force may cause concern in the comfort of wearing Skin+. The participants were asked to score the comfortable actuation they can feel as shown in Figure 4.2.2. Therefore, we select 0.361A as base current for the user study for the daily scenario.

Summary

After the two studies, we gathered qualitative feedback from participants. They were asked to comment on the experience of haptic sensation and comfort of wearing Skin+ on the skin. Most participants commented that they could feel the sensation as is mentioned above also. Subjects commented the sensation as "insects crawling up" (P01, P03, P05, P06), "someone tapping on me" (P03, P04), and "being gently poked" (P04).

4.3. User Study: Validation in Daily Scenario

To study the influence that Skin+ can provide for the real world, we conducted a user study in a daily scenario.

The user study was done in a given space familiar to the users to see if Skin+ can enable users to feel augmented as shown in Figure 4.3. Skin+ Array is used in the experiment based on the comment we got from the perception study. We assume our Skin+ can support different kinds of daily scenarios in collision avoidance:

Figure 4.6 User Study: Validation in Daily Scenario

1. In the darkness;
2. Blind Point;

Based on the scenarios, we have two scenarios for this experiment.

Participants

5 participants (2 females and 3 males, aged from 21 to 26, mean age = 23.2) were recruited from our institution. The participants all signed the contract form and none of them reported any health condition that could have affected their performance in this experiment. Three of them had done the previous perception study.

Method

In this experiment, the user wears one Skin+ on each upper-arm. The size is adjustable to better fit users. The procedure of the experiment will not be informed first. Participants need to sign consent forms to participate in the experiment.

- **Blind Point**

  In the first scenario, users are asked to sit naturally at the table, playing their phone. The experimenter randomly goes upward to reach for them (such as tapping on the shoulder) from their blind point to see if they can perceive through Skin+ before we reach for them. We discussed the results with participants.

- **In the Darkness**

  The second scenario is conducted in a $5m^2$ space. Users are asked to go straight towards the wall with eyes closed. The users are taken to the position without knowing exactly how far the position is to the wall. We want to observe the way they behave, they walk and they react to the Skin+ to see if they can perceive before bumping into the wall. We control the Skin+ Array worn on the user and talk with them.

Through this particular way, we can have a deep observation and spontaneous communication with the user in the space. After that, an open-ended interview to collect general comments about the system is conducted. The participants were asked about their feelings towards the sensation and whether they feel augmented or not.

Results

Scenario 1 has been done by three users. They confirmed they can perceive the Skin+ when they are playing the phones. They did not know what to react towards the Skin+ at first. Through three-time training, users were able to understand and perceive the person coming close.

Scenario 2 has been done by three users. One of the users started to walk more slowly when feeling the actuation started. Another user stopped as soon as felt the actuation. After average two-time training, all the users were able to stop before bumping to the wall through Skin+.

4.4. Discussion

The linear actuation of Skin+ Array was mostly commented by users as insects crawling over the forearm. If the direction is from down to up, it will give them an uncanny feeling of something is approaching. Also, the single actuation of Skin+ Array made the users feel being gently tapped by friends. For the whole experience, instead of spatial augmentation, they feel more about perception augmented from themselves. Users stated that "An object without direct contact to my body seems to be felt by my body. " and "It is not like my living space growing larger, but like the extension to my own perception.".

Also, we noticed the users have a different feeling based on the tightness of the base of Skin+ Array. If tight, users will regard the single actuation as pinch and multiple actuation as crawling. If loose, users will regard the single actuation as tapping and multiple actuation as slipping. This can be one additional parameter when we want to design the haptic sensation using Skin+.

Chapter 5
Conclusion

5.1. Conclusion

In this thesis, from the perspective of our research on the skin extension for augmenting users' sense, we designed, fabricated and developed a fabric-based modular programmable Skin+. In this thesis, we

- presented lightweight, modular on-skin interface;
- created a mechanism for reproducing the indirect contact with Skin+;
- fabricated motorless actuator for friction sensation;
- demonstrated an on-skin system more applicable to a large surface of the skin.

We describe the method to design and fabricate 3D-printed Skin+ modules. The process is done with commercially available materials and equipment. We selected and focused on a customized mechanical tactile stimulation with expressive sensation compared with vibrotactile actuators and electro-tactile interfaces.

Unlike prior haptic devices on the skin, Skin+ is more suitable for multistage control, less obtrusive and more applicable to a large surface. To have a fully functioning multistage control for both single modules and multiple modules' situation, we create a novel open-loop control system with designed circuit and codes so that the Skin+ module can present different degrees of expansion or contraction and can manage to hold in one certain position required during the actuation process. Considering from wearers' perspective, we combine and add the base material to act as an adjustable fixture to the Skin+ modules as well as keep the wearability of the Skin+ system.

This work also casts light on modular haptics on larger areas of the body where customizability and developability are needed. This work contributes to the new possibility of haptic augmentation for spatial perception.

5.2. Limitation

The limitation of Skin+ mainly lies in two aspects: SMA material and wearing material. While SMA material has expressive motion, its slow actuation rate may restrict the interaction type. Its high power consumption may lead to problems that we need reliable thicker wires for passing the high current. Although we can actuate it at a lower current such as 0.14A, the actuation turns out to be slow if we do that. Therefore, even we chose a low-temperature SMA, it still consumes a lot when actuated in a designed manner.

The other limitation is the wearing method. We hope there is an alternative material to let the wearing and actuating to be one compact thing having the potential to combine with sensing coherently in the future. Also, we want it to have the ability to have Shape-changing feature and can hold multi-stage of the changing progress, programmable, easy to wear on the body to deliver understandable expressive sensation.

5.3. Future Works

5.3.1 Multiple Body Sites

Variations for the prototypes are considered to fit into diverse body cites such as shoulders, necks and backs. We imagined a whole picture of another layer on the skin to be a new sense to the body, which is mentioned in Chapter 1. We want users to have high freedom to define the function for different part of the new organ. This can be explored in the near future.

5.3.2 Customizable Haptic Sensation

The shape of the auxetic structure is customizable for alternative haptic sensation and look on the skin. It is possible to let users design the type of haptic sensation they want to have through simple editing or drawing. Its developability is good.

5.3.3 Haptic Channels

Diverse haptic channels can give intuitively understandable sensation to users. Therefore we want to further combine the single actuation and multiple actuation with heat to create a rich experience.

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