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Haptic Stickers: Thin, Flexible On-Skin Haptic Devices

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Abstract

This thesis investigates the development of wearable tactile devices for human computer interaction (HCI). In situations, where both audio and visual channels are occupied, our skin can be used as a discrete channel for communication.
To date, interfaces that invoke non-vibrotactile sensations on the skin, such as light touch, pressure, stretch, etc., use motors or valves as actuators. This makes them heavy, bulky and incompliant, thus impractical for wearable use. We propose an alternative actuation mechanism based on shape-memory-alloys (SMA). SMA are very light, compact and quiet actuators with a higher weight-to-force ratio than traditional motors.
Together with an assembly of 3D-printed parts we create different wrist-worn tactile devices, called bracelets, that invoke rich sensations on the skin, such as pushing, rolling, tapping, pinching, scratching, dragging. These bracelets are small, lightweight and have a simple design and control interface.
In this thesis we demonstrate how to fabricate these tactile bracelets in a wearable form factor. We also describe how to work with SMAs to achieve better perception and overcome their heat issues. Finally, we present a user study to validate our designs. The study shows that users can distinguish different sensations, ones better than the others. For example, if the users worn ROLL bracelet, in 78% cases they would feel rolling sensation, whereas if the users worn PINCH bracelet, they would feel pinching in 63% cases. However the users tend to mix up pushing and tapping sensations with each other.
We close with a discussion of aspects that were not in scope of this thesis and thus deligate them into future work.

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Conventions

Throughout this thesis we use the following conventions.

Text conventions

For the purpose of politeness, first person plural form is sometimes used in the thesis.

Marginalia are included to summarize important aspects throughout the thesis.

This is an important aspect.

The whole thesis is written in American English.

Chapter 1

Introduction

Our skin is sensitive to a number of tactile sensations, ranging from simple vibration to more complex modalities, like stretching, pinching, pushing, pulling, tapping, scratching, dragging, etc.
Researchers have first tried exploring simple vibration sensation. To enable people to stay connected while on the go, a range of interactive wearable devices, such as smartwatches and -bands, have become commercially available. Commercial devices, such as Apple Watch and Motorola 360, embed vibration motors to communicate symbolic tactile messages to the wearer, supplementing the visual and auditory channels.
To overcome the limitation of the inherently small interaction space of these devices, researchers have proposed a range of new input and output techniques that leverage the size and tactile sensitivity of the human skin. Richer tactile feedback was achieved by a number of devices that move mechanical structures on the skin using motors, or valves. These and similar interfaces are presented, for example, in Je et al. [2017], He et al. [2015], Strasnick et al. [2017], Pece et al. [2017], Ion et al. [2015]. The main drawback of these devices, however, is that the weight, bulkiness, and rigidness of the used motors limits the practicality of such devices in wearable applications.
In the work of Gemperle et al. [1998] (Design for Wearability) a wearable device should fulfil a list of requirements to be considered as wearable. The device should:

- be comfortable;
- be lightweight;
- not interfere with human movements.

However the majority of the devices described above do not conform to the body and in this thesis a new solution will be proposed.
Chapter 2 will introduce a number of devices, which are able to create haptic sensations on the skin. After making the gap analysis, Chapter 3 will introduce haptic bracelets that use different actuation mechanism to invoke different tactile sensations on the skin. Then, a user study in Chapter 4 will be conducted to evaluate them with regard to comfort and perceptibility. The last Chapter 5 will summarize this Thesis and briefly describe aspects that will be addressed in the future.

Chapter 2

Related work

This chapter will give an overview of different haptic devices that are able to invoke different haptic sensations on the skin. We differentiate them based on a criteria, which type of actuator they use.

2.1 Haptic devices based on traditional actuators

Dragging sensation
TactoRing (Je et al. [2017]), shown in Fig.2.1 represents a wearable haptic interface that is worn on a finger. This prototype consists of a DC motor, gears, a moving tactor and IR sensor, which tracks and encodes the relative motion of the gears in order to infer the tactor location around the finger. TactoRing drags the moving tactor in 1-D around the finger creating the dragging sensation on the skin.

Tapping sensation
PneuHaptic (He et al. [2015]), shown in Fig.2.1, is another wearable haptic device that is worn on a forearm. It consists of an array of pneumatically activated air chambers, a small air compressor, solenoid valves and a control board. Due to its design this device is able to produce different sensations on the skin and one of them is tapping, which is achieved

by changing the activation pattern of chambers. Also other haptic devices, described in Li et al. [2008],Jin et al. [2014] and Stanley and Kuchenbecker [2012], can produce the tapping sensation on the skin.

Brushing sensation
BrushTouch (Strasnick et al. [2017]), shown in Fig.2.1, is worn on a wrist and consists of a wrist band, six DC motors attached to it and brushes attached to the motors. As the motors rotate, the brushes brush against the skin creating a unique haptic sensation.

Poking sensation
MagTics (Pece et al. [2017]), shown in Fig.2.1, is worn on the wrist and consists of electro-magnetic actuators, coils, magnets, steel latching plates, heat sinks and flexible 3D-printed case. This haptic device uses magnetic actuation to invoke poke sensations on the skin. One of the biggest limitations here is the excessive Joule heating, which is generated during repetetive frequent device actuations.

Haptic devices based on traditional actuators use motors, valves to move physical structures in order to invoke different haptic sensations on the skin.

Squeezing sensation
Squeezeback (Pohl et al. [2017]), presented in Fig.2.1, is worn on the wrist and consists of inflatable straps that are activated using pneumatics. This general concept is able to invoke rather simple squeezing sensations on the skin, which are supported by another haptic devices, such as one described in Chinello et al. [2014].

Stretching sensation
A haptic device, proposed in Ion et al. [2015], is worn on the user's forearm and consists of round actuation area (rotating diaphragm), a motor, a driven wheel, a moving tactor and a magnetic encoder encapsulated into this diaphragm, as depicted in Fig.2.1. This actuation area creates the stretching sensation by dragging the mentioned tactor across the skin. Not only this device is able to provide the stretching sensation, but also the one described in Prattichizzo et al. [2010].

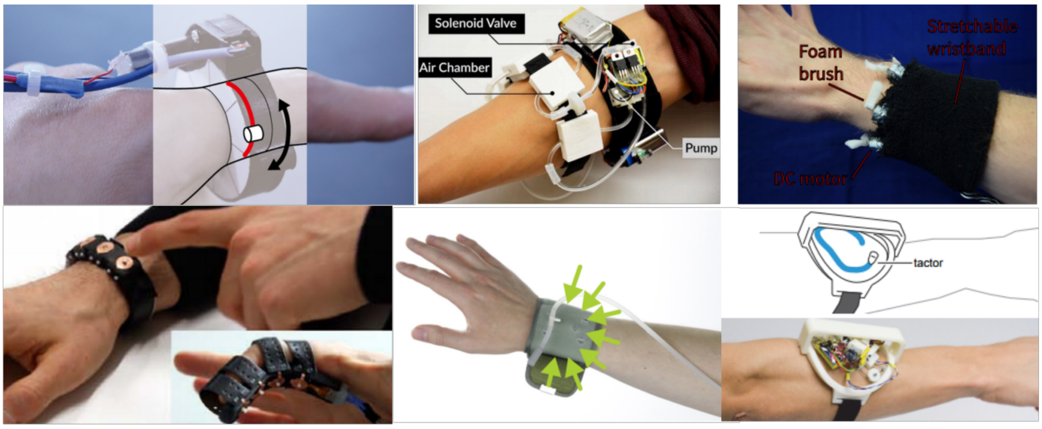

Figure 2.1: Haptic devices based on traditional actuators. From top to the bottom, from left to the right: Je et al. [2017], dragging, DC motor; He et al. [2015], tapping, pneumatic valves; Strasnick et al. [2017], brushing, DC motor; Pece et al. [2017], poking, electro-magnetic actuators; Pohl et al. [2017], squeezing, pneumatics; Ion et al. [2015], stretching, geared motor.

2.2 Haptic devices based on smart material (SM) actuators

From now, we want to explore another actuation possibility by using smart materials, instead of using traditional motors or valves. A SM is a type of designed material that significantly changes one or more of its properties by applying external stimuli, like stress, moisture, temperature, electric and magnetic fields.

Stretching sensation
The Tickler (Knoop and Rossiter [2015]), shown in Fig.2.2, is worn on the forearm and consists of a wrist band, tactile moving bars, SMA wires , which is one type of SM, and control board. By connecting the bars with the SMA wires in a smart manner and by applying current through them, the wires start to contract, which results in moving the bars against the skin surface. This provides the user with the stretching sensation on his skin.

Current trend in haptics is to use actuators that are based on smart materials.

Squeezing sensation
HapticClench (Gupta et al. [2017]), shown in Fig.2.2, is another haptic device based on SM actuator. It is worn on

Figure 2.2: Haptic devices based on SM actuators. From left to the right: Gupta et al. [2017], squeezing, SMA; Knoop and Rossiter [2015], stretching, SMA.

either forearm or a finger, and consists of a textile bracelet wrapped around the forearm and SMA wire programmed into a spring. When current is fed through it, the SMA wire contracts around the forearm creating a very simple basic squeezing sensation on the skin. Haptic interfaces described in Suhonen et al. [2012b], Suhonen et al. [2012a] can also create the squeezing sensation.

2.3 Towards our approach

User studies show that wearable haptic feedback devices from this chapter fulfil their primary requirements. They are able to provide a user with different haptic sensations on the skin.
In case of the devices that are based on traditional actuators, many haptic sensations can be covered, so a quite rich vocabulary can be created. However these haptic devices have major drawbacks:

- Bulkiness (motors and other parts);
- Electro-mechanical noise (air compressors, motors);
- Relatively low lifecycle (motors operate on higher frequences, thus enabling negative responses after lengthy exposure);
- Low comfort (the user is aware of something worn on its body).

In case of the devices that are based on SM actuators, the overall bulkiness is reduced to a certain extent. However these devices are still bulky and what is more important, they cover only a narrow range of possible haptic sensations, so only a weak vocabulary can be obtained.

Approach presented in Chapter 3 aims at creating haptic bracelets that use actuation technology based on SM. Moreover, they should create a large haptic vocabulary compared to the existing prototypes based on SM from this chapter. They also should not have the disadvantages, which are typical for the existing prototypes based on traditional actuators. Finally, they should be easy exchangeable.

Motors and valves are bulky, they are heavy and not flexible. SM-like actuators are compact, lightweight and flexible. We will use them in our work.

Chapter 3

Haptic bracelets

The goal of this chapter is to find an actuator that better fulfils the requirements of wearable tactile devices. First of all, small and compact devices should be preferred over big and large ones. Second of all, lightweight devices are more wearable than heavy ones. Finally, comfort factor should be taken into consideration, because it is important to be able to wear devices for a long period of time without feeling any discomfort. Pacchierotti et al. [2017]
In this respect, choice of actuators is crucial, so we want to investigate different smart materials, compare them and pick the most promising one, which ideally fulfils all requirements for our future haptic bracelets.

3.1 Overview, comparison and choice of SM

We want to categorize SM by the external stimuli. There are lots of possible SM, but we want to explore only a subset of those that can be handled in a controlled fashion. Fig.3.1 depicts this principle. Every abbreviation corresponds to a leaf of this tree and represents an existing SM. Let us briefly discuss each of them.

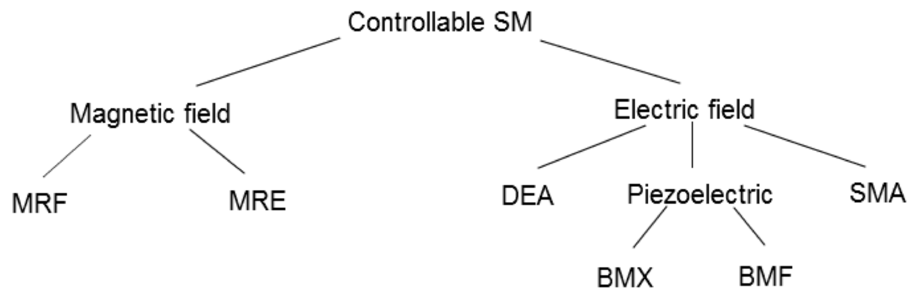

Figure 3.1: SM categorization.

MRF and MRE
Magnetorheological fluid (MRF) is a smart liquid. When subjected to a magnetic field, it greatly increases its viscosity and transforms into stiff paste within seconds. The yield force is proportional to the magnetic field intensity. This SM is controllable, because the magnetic field intensity can be adjusted by an electromagnet. MRF is used in actuators as a damper (Lai and Liao [2002]) or for force feedback tasks (Winter and Bouzit [2007]). For example, in Blake and Gurocak [2009] it was used to build a haptic glove that could convey stiffness information of a virtual object to a user.

MRF and MRE are passive actuators, which is not sufficient to use them in our case.

Magnetorheological elastomers (MRE) are solid counterpart to MRF. They are composite materials that consist of an elastomer matrix and magnetizable particles. When the magnetic field is applied, the magnetic particles are polarized and exert forces on one another, which causes the material to stiffen. When the magnetic field is switched off, MRE returns to its original softer state. It was used in Böse et al. [2012] to build actuators for valves.
These two types of SM are not active actuators that can move physical parts without complex mechanical structures, which is a limitation.

DEA
Dielectric elastomer actuators (DEA) is a SM that undergoes large strains up to 300% when applying an external electric field. This SM acts like an actuator by using the following working principle. An elastomeric film is covered

on both sides with electrodes that are part of an electrical circuit. This is a volume-preserving SM and by applying voltage the electrostatic pressure starts acting. Due to this compression the elastomer film contracts in the thickness direction and expands in the film plane direction. After the circuit is disconnected, the elastomer film gets to its original position. DEA are widely used in pneumatic automation technology as actuators for valves (Giousouf and Kovacs [2013]). In haptics they were used in Knoop and Rossiter [2014], for example, to move physical structures that apply shear forces to skin.

DEA require high voltages and frequencies. It can be dangerous to use them in wearables.

SMA

Shape-memory alloy is an alloy that remembers its shape and, when deformed, goes back to its programmed shape by applying heat or current. Programming is done by curving a wire into some shape and then applying very hot temperature (500-600 degree Celcius), until the wire gets dull red glow. For example, if the SMA wire was programmed into a spring, then it would be able to contract when passing current through it.

The BioMetal Fiber (BMF) [1] is one type of SMA that is considered to be a muscle-like actuator. Under normal conditions it is soft and pliable, whereas it contracts and gets very sharp and stiff, when current is fed through it. Its most interesting properties are:

- The maximum contraction is about 5% of its original length;
- Ability to produce force up to 144 grams;
- It can be repeatedly used $< 10^6$ number of times.

BioMetal Helix (BMX) [2] is another type of SMA, which is a biometal micro coil. This SM acts like a linear actuator in terms of linear motion. Elongated at room temperature up to 250% of its original contracted length, BMX can:

[1] Artificial Metal-Based Muscle for Long Stroke Actuators. BioMetal Fiber. `http://www.toki.co.jp/biometal/download/downloadfiles/BMF_Catalog_140217.pdf`

[2] Artificial Metal-Based Muscle for Long Stroke Actuators. BioMetal Helix. `http://www.toki.co.jp/biometal/download/downloadfiles/BMX_Catalog_140217.pdf`

- contract up to 150% of its original length;
- contract with force up to 30 grams;
- be repeatedly used any number of times.

Comparison and choice of the most suitable SM
After the brief introduction of SM, we can compare them in order to find out, what is the most promising one to be used as an actuator for the haptic bracelets later on.
First of all, we want to exclude a brach from Fig.3.1 that is controlled by the magnetic field, because in order to create it, you still need to have an electric field first. Additionally, a corresponding electrical circuit will be bulkier, because of extra components, such as coils etc. Moreover, MRF and MRF are those kinds of SM that are not very suitable, because this is either liquid or an array of magnetic particles. You can control it, but it is hardly applicable for the haptic bracelets we want to design.

SMA is the most attractive option to use it as an actuator. More specifically we will be using BMX, because it is compact, lightweight, flexible and can produce good contraction force and good range of motion.

Let us have a look at another branch from Fig.3.1 that is controlled by the electric field instead. First, we exclude the DEA, because it is quite hard to control them and they are just too dangerous to use in context of HCI (they require very high voltages and frequencies).
Thus, the remaining SM that could be used as an actuator is SMA. BMF is an attractive option in terms of the generated force, but it produces very limited range of motion. For instance, if you want to generate 2 centimetres long contraction, then you will need BMF to be 50 centimetres long, whereas BMX will have to be only 4 centimetres long to achieve the same result. So BMF can get quite bulky, which we want to avoid. BMX fulfils all requirements, like good contraction force, great range of motion, while being very compact at the same time. This is sufficient to use it as an actuator in all future haptic bracelets.

3.2 The Joule heating and ways to solve it

After the decision had been made to use BMX as an actuator, a pilot haptic prototype was created to test BMX properties on the skin and find possible issues. Fig.3.2 shows

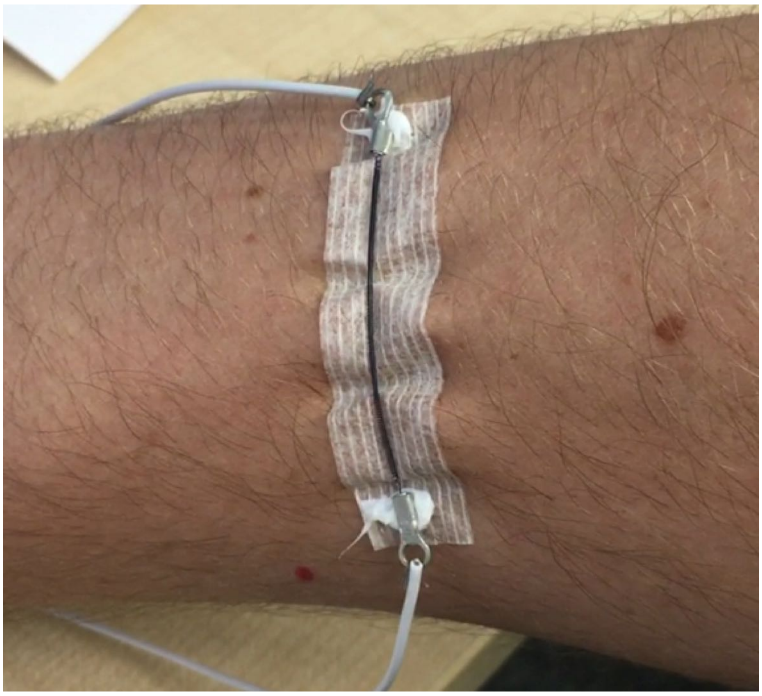

Figure 3.2: A pilot haptic prototype based on a single BMX in the contraction phase.

how it looks like in the contraction phase. As you can see from the picture, the prototype consists of an isolation layer and a single BMX, which is fixed from both sides. Thus, the only way for BMX to contract is to pull the skin. This creates a semi-pinch sensation, which was a good first result.
However an important issue was found, which disturbs the perception drastically. When current is fed through BMX, its temperature can get very high depending on an amperage. Since no electrical isolation is provided for its surface, some measures have to be taken to prevent accidental contact, because we want to use BMX close to the skin and letting it cool faster will give us faster response.
First, we tried to use *Arctic Silver 5* thermal paste to solve the heat problem. *Arctic Silver 5* has high-density filling of micronized thermally conductive silver particles. It is used in cooling solutions for high-power CPUs and high perfomance heatsinks [3]. We added an additional isolation layer

When current is fed through BMX, it heats up to 70 or more degrees depending on an amperage. If put directly on the skin, burning sensations occur. Cooling techniques should be applied to let it use close to the skin.

[3] Arctic Silver 5. High-Density Polysynthetic Silver Thermal Compound. http://www.arcticsilver.com/as5.htm

Arctic Silver 5 thermal paste showed unsatisfactory results.

beneath the one from Fig.3.2. In between those isolation layers we put *Arctic Silver 5* and again tested the prototype against the heat problem. However no satisfactory results were obtained. In order for the thermal paste to work properly, it needs to be programmed for several hundreds of hours under the high temperature conditions. Furthermore, after it was programmed, *Arctic Silver 5* is only able to slightly decrease the temperature. These facts led us to explore further alternatives.

Conduction and convection cooling
Heat has a property that it always tries to move from one medium, which is hotter, to another cooler medium. There are two most common techniques, which ensure that heat is transferred from a heat-generating device to another cooler medium. These techniques are:

- conduction and
- convection cooling.

Conduction cooling [4] transfers heat within a device from a hotter part to another cooler part by direct contact. Usually, the cooler part of the device is a heatsink, which is in contact with the hotter part, thus enabling heat to be absorbed. Convection cooling [5] transfers heat by means of the natural or forced air flow, which surrounds the device. When the air contacts heat, its density changes, which in turns enables the heat transfer. The main requirement here is that the air, surrounding the device, should be cooler than the device itself.
The advantage of convection cooling is that it does not require any bulky hardware like a heatsink, as long as this is the natural air flow. As a next step, we wanted to explore these two cooling techniques for our use case. Consequently, a next prototype was designed, shown in Fig.3.3 to

[4] What are the differences between Conduction, Convection and Radiant Cooling of Power Devices? http://power-topics.blogspot.de/2007/11/what-are-differences-between-conduction.html
[5] What are the differences between Conduction, Convection and Radiant Cooling of Power Devices? http://power-topics.blogspot.de/2007/11/what-are-differences-between-conduction.html

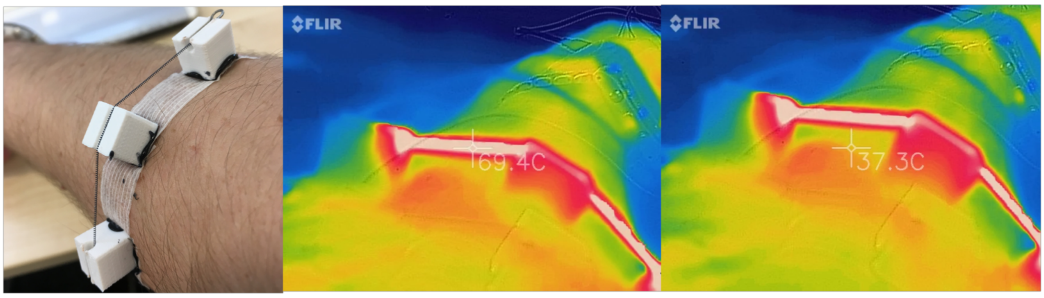

Figure 3.3: Convection cooling. From left to the right: a prototype that should eliminate the heat problem; BMX temperature during the contraction phase; skin temperature during the contraction phase.

the left. In this scenario a component that generates heat is obviously BMX. Conduction cooling aspect here is realized by means of three 3D-printed white terminals that act like not very efficient heatsinks. Convection cooling is done here by means of adding the height to these terminals. In such a way there is a gap between BMX and the skin, which creates the natural air flow. This prototype was then put on the skin and tested against the known issue. From the first sight, results were satisfactory and no traces of heat were detected on the skin, while the prototype could still deliver a semi-pinch haptic sensation.

Convection cooling: lift BMX above the skin to create the natural air flow. Conduction cooling: attach BMX to heatsinks that will absorb the heat.

To formally prove this hypothesis we used a thermal camera *FLIR*, which was attached to an *iPhone*, together with the corresponding *FLIR ONE App*. With this setup we were able to get heat distribution pictures, shown below. In general, the heat distribution is mapped to different colors, where dark blue corresponds to the coldest temperature, light red to the hottest one, and everything left exists in between.

Fig.3.3 represents a setting, where BMX is triggered via a hardware button numerous number of times. In order to create the most stressful condition for BMX, there was no relaxation phase in between two consequent button pushes, meaning that BMX was only contracting. This was done to see, how hot BMX can actually get under the conditions, which violate the operating ones. Fig.3.3 in the middle shows a snapshot in time, when BMX temperature rised to almost 70 degrees Celcius shown in light red. If the above described stressful conditions continued to be applied, then BMX temperature could rise even up to 100 degrees Cel-

BMX temperature is rising to high degrees, however skin temperature stays normal.

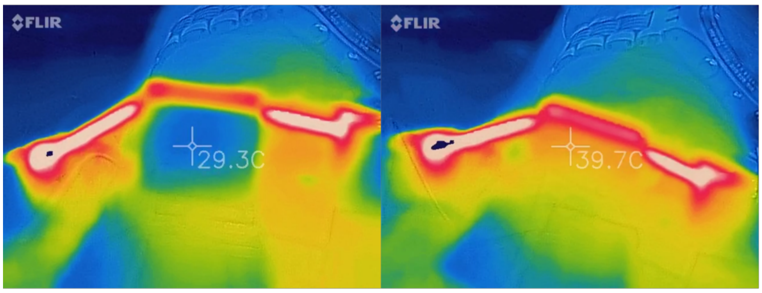

Figure 3.4: Conduction cooling. From left to the right: heatsink temperature during the contraction phase at time t_1; heatsink temperature during the contraction phase at time $t_2 > t_1$.

cius, which is not shown in this picture.
Fig.3.3 to the right represents the same setup from before, but further in time and focused on skin temperature. While BMX temperature is being rised, skin temperature is staying the same at approximately 37 degrees Celcius shown in orange. This proves the hypothesis from above in terms of convection cooling.

Heatsink temperature is slowly rising. Heat transfer is transitive: from BMX to the heatsinks to the skin. This is a very slow process.

We then repeated the same procedure from the beginning, but now the focus was on conduction cooling aspect of the hypothesis. Fig.3.4 to the left shows a snapshot in time, after BMX was contracted for the first time. Heat distribution shows that everything (except BMX) is cool, including three terminals. The temperature of the terminal in the middle is 29.3 degrees Celcius shown in blue. However with time passing by, heat is slowly transferred from BMX (hotter part) to the terminal (cooler part). Fig.3.4 to the right demonstrates, how the heat distribution changed after some time. Now, the terminal became hotter with 39.7 degrees Celcius shown in orange. Thus we get the transitive heat transfer (from BMX to the terminals to the skin). Taking into account the fact, that BMX is usually activated for a several hundreds of milliseconds, temperature on the skin will never reach its dangerous mark. This proves the hypothesis from above in terms of conduction cooling. As a last remark regarding conduction cooling, tubes surrounding BMX can also be used as heatsinks.

3.3 Design process of different Haptic Bracelets

After the heat problem for BMX had been solved, it became possible to use it as an actuator. BMX provides great range of motion, however this motion is linear. To avoid this limitation on the path towards creating reach vocabulary of haptic sensations on the skin, a decision was made to use a simplified automaton idea. An automaton can be a mechanical structure, where a certain predefined complex motion pattern is triggered by some actuator, like a human's arm, or a motor. This idea was projected on our use case and we decided to create different mechanical structures, which encode different haptic sensations on the skin. These structures consist of an assembly of 3D-printed parts together with its core component BMX, which triggers them to provide a specific sensation on the skin. To make these structures wearable, we attached them to different wrist bands, so that they became haptic bracelets. Let us have a closer look to how a certain haptic bracelet was designed to deliver some sensation on the skin.

BMX motion is linear, which is a limitation. To create reach haptic vocabulary we use BMX to trigger moving physical structures.

To design the haptic bracelets, *OpenSCAD* software was used together with *Cura* to actually print them on different 3D-printers, such as *Ultimaker 2 Extended+*, *Ultimaker Extended 3* or *Prusa i3 Mk2*. Each haptic bracelet utilizes both approaches against the heat problem, described in the previous section.

PUSH bracelet

Our skin is able to detect a pushing sensation on its surface. A human perceives it at most, when something moves perpendicularly to the skin surface, then touches it and continues moving in this direction, until the resistance gets too high. PUSH bracelet, presented in Fig.3.5, implements this idea. This bracelet consists of the following components: (1) - a wrist band; (2) - two terminals; (3) - BMX; (4) - a board; (5) - a beam; (6) - a nail; (7) - a spring; (8) - two wires. It is important that the only moving part in this bracelet is the nail. That is why the wrist band is not elastic, as well as the terminals are attached to the plastic board. If any of those components violated this condition and, if the nail touched the skin and tried to continue its motion, then

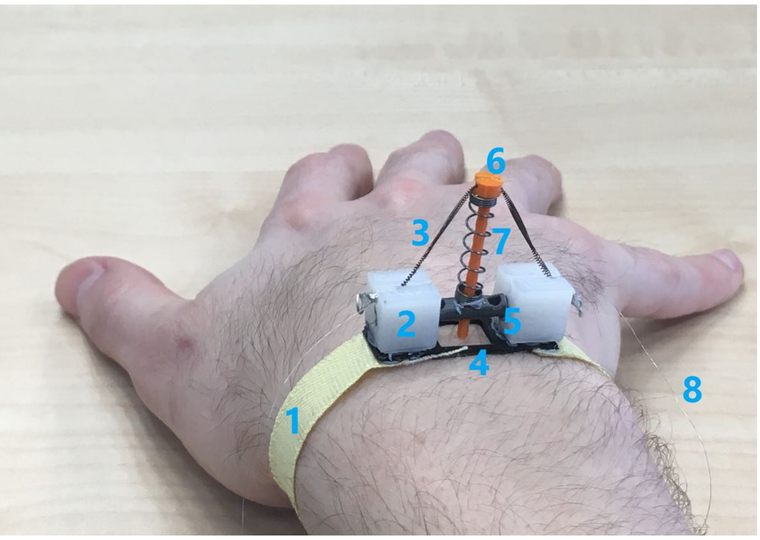

Figure 3.5: PUSH bracelet and its components.

the whole system would become unstable and the pushing sensation would be weak. To make it noticeable we should guarantee that every other component is stable and the nail moves strictly in the vertical direction. This is achieved by putting the beam in parallel to the skin surface and making a hole in this beam perpendicular to the skin surface accordingly. When current is fed through the wires and BMX, the last one contracts and pushes the nail down until it touches the skin. When current is not fed anymore, BMX relaxes and lets the spring pull the nail back up. In such a way the pushing sensation can be repeated any number of times.

Whenever we use BMX, we should ensure that there is some pulling mechanism to elongate BMX after contraction. In case of PUSH bracelet this is a spring.

ROLL bracelet
If something is initially attached along the skin and then parts of the object become gradually unattached, a human can detect it. ROLL bracelet, presented in Fig.3.6, implements this idea. This bracelet is a little bit bulky in terms of length, but we wanted to design it and see how users perceive it, because the rolling tactile sensation has not been covered yet in research dedicated to wearables. So it consists of the following components: (1) - a wrist band; (2) - a rolling element; (3) - BMX; (4) - two wires. It is again important that the wrist band is not elastic, otherwise a terminal

Rolling sensation has not been covered in wearables research until now.

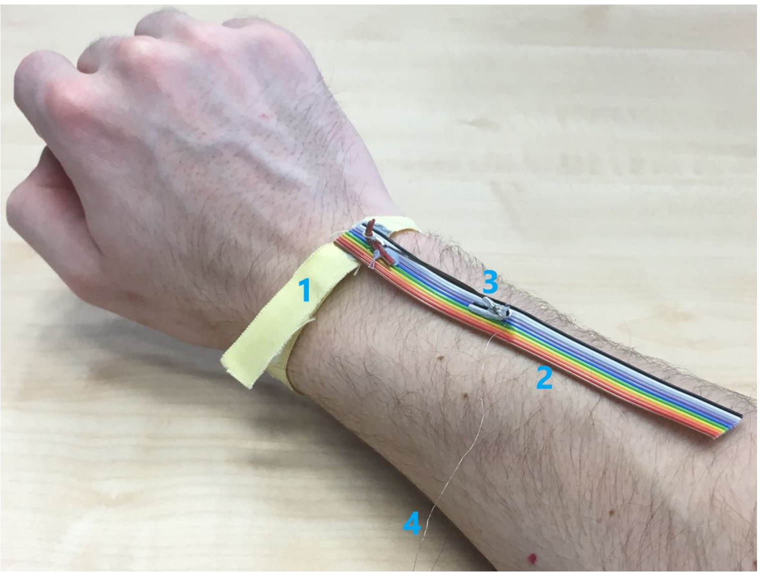

Figure 3.6: ROLL bracelet and its components.

connected to the band from one side will eventually try to pull it while BMX is being contracted. This undesired effect will prevent the rolling element from realizing its full potential, thus the overall perception will decrease. The rolling element is flexible and attached to the skin. When current is fed through the wires and BMX, the last one contracts in the direction of the attached terminal and parts of the rolling element gradually get unattached. When current is not fed anymore, BMX relaxes and the rolling element gets to its original position.

TAP bracelet

Our skin is capable of detecting a tapping sensation on its surface too. This sensation can be categorized as a soft touch, where the touching area is not localized at some point, but is rather distributed. TAP bracelet, presented in Fig.3.7, implements this idea. There are some other haptic interfaces that realize the tapping sensation, however our bracelet does a soft and light touch. A human has a unique set of sensory receptors that can detect the light touch easily. This bracelet consists of the following components: (1) - a wrist band; (2) - foundation; (3) - two terminals (white, orange); (4) - BMX; (5) - a rotating element; (6) - a tapping

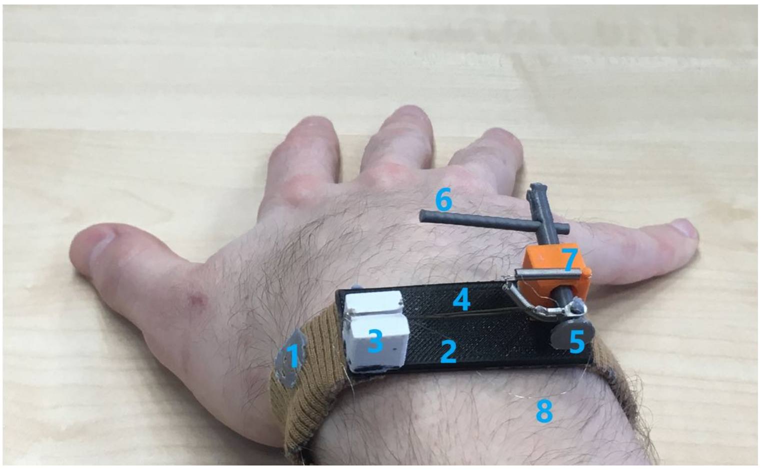

Figure 3.7: TAP bracelet and its components.

stick; (7) - a spring system; (8) - two wires. The wrist band here is elastic, however the foundation is stiff to exclude undesired movements, which will decrease the bracelet's perfomance. The key component in this bracelet are the rotating element and the tapping stick, which is inserted into the rotating element. When current is fed through the wires and BMX, the last one pulls an attachment point of the rotating element in the direction of the fixed white terminal. Since the attachment point is located on the rotating element, we get the counter-clockwise rotational movement, and because the tapping stick makes the same rotational movement, a point is reached, where the tapping stick taps the skin. When current is not fed anymore, BMX relaxes and lets the spring system pull the tapping stick back up. In such a way the tapping sensation can be repeated any number of times.

TAP bracelet does a soft, light and distributed touch that can be interpreted by a unique set of sensory receptors. Spring system ensures that a tapping stick (6) will return to its original vertical position after contraction.

PINCH bracelet
A pinch sensation is a very unique sensation on the skin, which our brain can easily interpret. This sensation can be described by fixing two points on the skin and pull them towards each other. PINCH bracelet, presented in Fig.3.8, implements this idea. This is the only prototype that actually deforms the skin. Other haptic interfaces require a lot of force to, for example, stretch the skin. Stretching the skin is a common effect, however we do here pinching, which

Figure 3.8: PINCH bracelet and its components.

is a more unique effect. This bracelet consists of the following components: (1) - a sticker; (2) - three wheels; (3) - two terminals; (4) - two wires. This bracelet made in form of a sticker can be seen as an upgrade of the pilot prototype from Fig.3.2. It is a quite simple, but as results will show, very effective prototype. Three wheels are glued to the sticker in order to simulate fixing three points on the skin. BMX terminals are also glued to the sticker from both sides, so the only way for BMX to contract is to pull the attached points towards each other. When current is fed through the wires and BMX, the last one contracts and executes two pinches between the neighboring wheels. When current is not fed anymore, BMX relaxes and since the skin stretches back, the whole system returns to its original state. This sticker still needs some work to be done to be called a bracelet, because physical context is needed to have attachments to the skin.

PINCH bracelet deforms the skin easily without applying much force, which is done, for example, in other interfaces that stretch the skin.

SCRATCH bracelet
Another unique sensation on the skin is a scratching sensation. It can be described by fixing a point with rough texture, for example a human's nail, on the skin and start moving this point along the skin slightly and temporar-

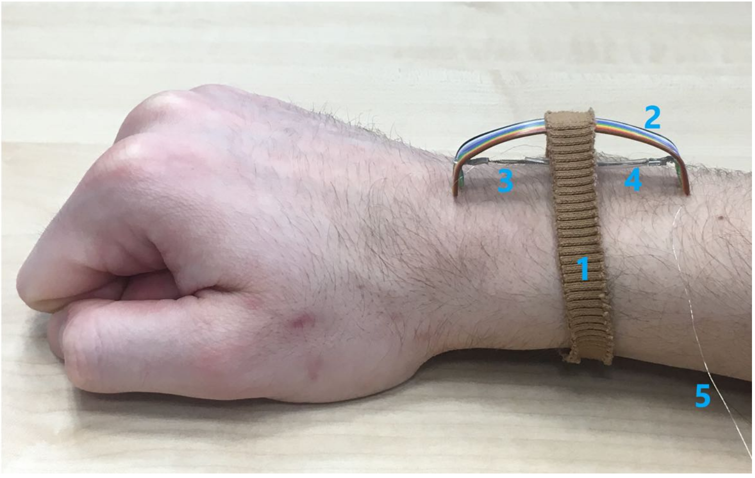

Figure 3.9: SCRATCH bracelet and its components.

SCRATCH bracelet is a pain effect, which is used in a lot of therapeutical interfaces to distract people from some activity. By modifying the edge of the bracelet, different levels of pain can be achieved.

ily modifying its integrity. SCRATCH bracelet, presented in Fig.3.9, implements this idea. This is our pain effect. Pain can be sensed by the skin effectively and it is used in a lot of therapeutical interfaces to distract people from some activity. Thus this is also an interesting modality in context of HCI. By modifying the edge of this bracelet we can cause either more or less pain. This bracelet consists of the following components: (1) - a wrist band; (2) - a scratching element; (3) - BMX; (4) - a tube; (5) - two wires. The wrist band in this case is elastic and the scratching element is flexible with rough texture on its ends to simulate, for example, a human's nail. Furthermore, these two components are perpendicular to each other. It was designed in that way to make BMX independent of the wrist band resistance. Moreover, in order to utilize the scratching sensation more efficiently, the area on the skin should be more or less flat. When current is fed through the wires and BMX, the last one pulls both ends with rough texture towards each other, thus creating the desired sensation. When current is not fed anymore, BMX relaxes and the system returns to its original state. As you can see from the picture, BMX in this bracelet is located quite close to the skin, thus creating a risk of accidental contact. By applying the techniques from the last section against the heat, such as creating more gap between BMX and the skin, and by packaging ineffective part of BMX into the tube, the SCRATCH bracelet remains

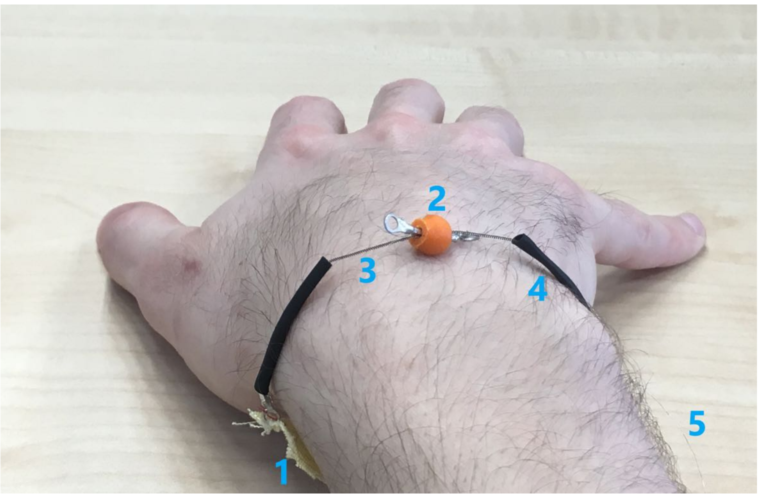

Figure 3.10: DRAG bracelet and its components.

safe.

DRAG bracelet
A dragging sensation on the skin is created, if there is a feeling that something moves along the skin's surface. DRAG bracelet, presented in Fig.3.10, implements this idea. This bracelet consists of the following components: (1) - a wrist band; (2) - a dragging element; (3) - two BMX; (4) - two tubes; (5) - four wires. This prototype realizes 1D back-and-forth dragging movement. Each BMX is attached to the wrist band from one side, and to the dragging element from the other side. The wrist band is not elastic to ensure that the only moving component is the dragging element. The bracelet operates in two differential phases. When current is fed through the corresponding wires and the first BMX, the last one pulls the dragging element in the direction of its fixed end that is attached to the wrist band. Since the dragging element is made in form of a sphere, this creates a nice perceivable dragging sensation on the skin. When current is not fed anymore through the wires and the first BMX, the first BMX relaxes and the second phase starts. During the second phase everything from above is repeated for the second BMX, which pulls the dragging element in the other direction. Ineffective parts of both BMX are again put into the tubes to avoid accidental contact with the skin. Even

DRAG bracelet is a differential system, where a pair of BMX is used to better control the position of a dragging element (2). This creates 1D motion, however if two pairs of BMX were used, it would be possible to create 2D motion.

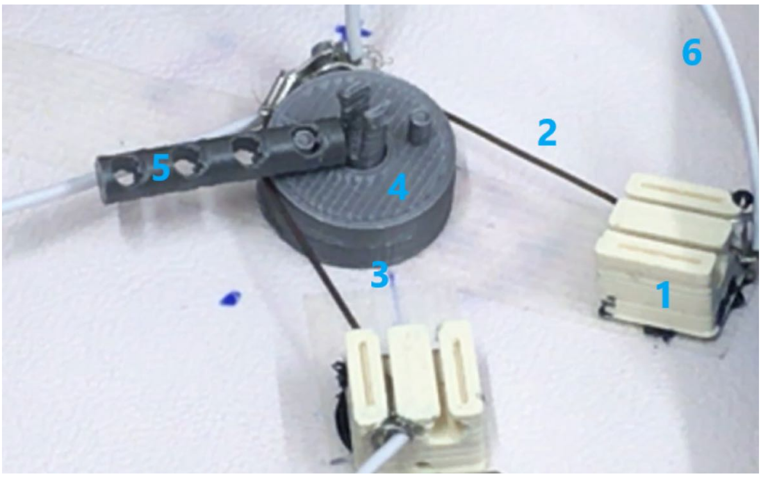

Figure 3.11: BRUSH prototype and its components.

though this interface creates 1D movement, it is a matter of adding another pair of BMX to create 2D motion.

Other haptic prototypes

BRUSH prototype is a differential system again. With filament insertions within a brushing element (5) it should be possible to brush on the skin's surface by rotating a rotational element (4) in clock- and counter-clockwise direction.

During the research several other prototypes were designed to extend vocabulary with haptic sensations on the skin. However they were not tested on the skin, which will be adressed in the future work.

Fig.3.11 represents a prototype to invoke a brushing sensation on the skin. This prototype consists of the following components: (1) - two terminals; (2) - two BMX; (3) - fixed base in form of a cylinder; (4) - a rotational element in form of a cylinder; (5) - a brushing element without filament insertions; (6) - four wires. This haptic prototype is again a differential system, which creates a rotational movement back-and-forth. When current is fed through the first BMX and its corresponding wires, BMX pulls an attachment placed on the rotational element in the direction of its terminal. Since the brushing element is attached to the rotational element, it also rotates either in clockwise or counter-clockwise direction. If the filament insertions were injected into wholes of the brushing element long enough to touch the skin, then a user would feel a brushing sensation. When current is not fed anymore through the wires and the first BMX, the first BMX relaxes and everything from above is repeated for the second BMX, which pulls the

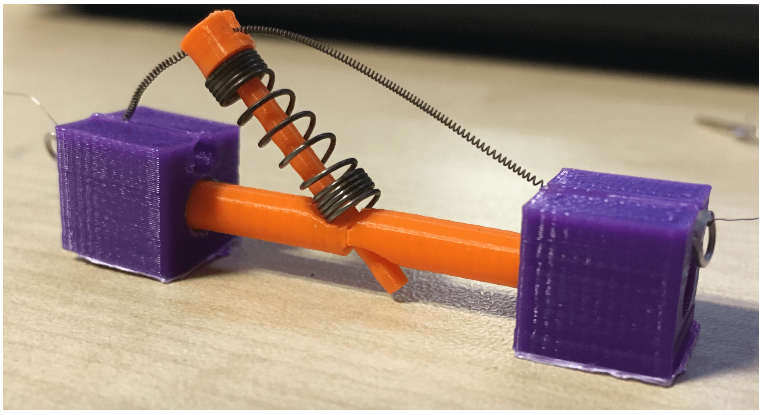

Figure 3.12: STRETCH prototype and its components.

attachment placed on the rotational element in other direction.

We also wanted to investigate, how a unique stretching sensation can be invoked on the skin. To create this sensation an object needs to move ideally almost parallel to the skin's surface. Then, after it collides with the skin, it tries to continue its motion, but since it moves almost parallel to the skin, it actually stretches it. Fig.3.12 shows one idea of how this could be potentially designed. This prototype is actually a tilted version of PUSH bracelet from Fig.3.5. However it exhibits three main disadvantages. First of all, a pushing nail is not sufficiently tilted. Second of all, the interacting area of the nail is too small and not flat to be able to stretch the skin. At last, the way, how BMX interacts with the nail, does not allow BMX to fully realize its motion range potential.

STRETCH prototype is a tilted version of PUSH bracelet. However it would be better to use a modified version of DRAG bracelet to stretch the skin by making the dragging element flat, rubber and of bigger area.

Another idea to create the stretching sensation would be to slightly change DRAG bracelet from Fig.3.10 by making a dragging element flat and rubber. While moving back-and-forth, it should grab the skin and stretch it. This idea will be also explored in the future work.

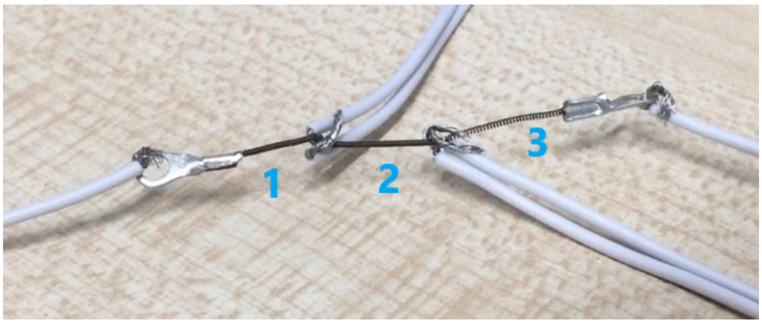

Figure 3.13: Partial BMX contraction (2/3 sub paths were consequently contracted).

Another BMX properties
During the research another interesting BMX property was discovered. It is actually possible not only to contract the whole BMX, but also sub parts of it, called sub paths in the following. Depending on between which two points voltage is applied, a sub path between only these two points is activated. Fig.3.13 shows this effect. Here BMX was divided into three equal sub paths, where two of them were contracted one after another. As a result, BMX only shrinks in 2/3 of its length. With this property BMX becomes more fine-grained and it also becomes possible to create new interesting spatio-temporal patterns on the skin. As an application, if there was a longer BMX and it was divided into a number of sub paths, the traditional PINCH bracelet from Fig.3.8 could be used in a more interesting way. The bracelet could be programmed in such a way, that different sub paths were activated at different times in a unique order, encoding some information. This would result in a moving pinching sensation on the skin.

New BMX property was discovered. It is possible to contract not only the whole BMX, but also sub parts of it. This makes BMX more fine-grained and opens space for creating new spatio-temporal patterns.

3.4 Control system and its parameters

In this section we will describe, how a system for controlling the haptic bracelets looks like, which components it is comprised of, as well as what parameters can be controlled and what they actually influence. Fig.3.14 shows, how the control system is designed.

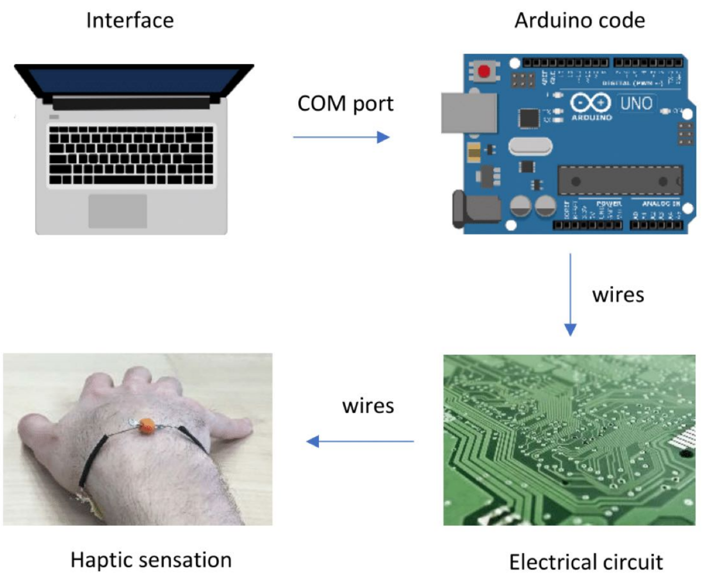

Figure 3.14: A system for controlling the haptic bracelets.

Control system
If a user wants to trigger a haptic bracelet, he first interacts with a graphical user interface, running on a computer. In the second step all input data is merged together into a Byte stream and sent over the COM port to Arduino microcontroller. Then, a corresponding *Arduino .ino program* from Fig.3.14 splits this data into blocks, analyzes them and activates an electrical circuit. We need the electrical circuit, because Arduino microcontroller is able to output only 5V and very low current, which is not sufficient for our purpose. In the last step the electrical circuit becomes closed and current is fed through wires and BMX, which makes it contract and activate the actual bracelet.
During the research there was a need to implement different uses cases, which required different logic of the electrical circuit from Fig.3.14. We used two types of it:

Electrical circuit with relay logic allows to implement differential systems more easily, than based on transistor logic. However it is not possible to control the speed of contraction.

1. with relay or
2. transistor logic.

Fig.3.15 shows, how the first type is implemented. Typi-

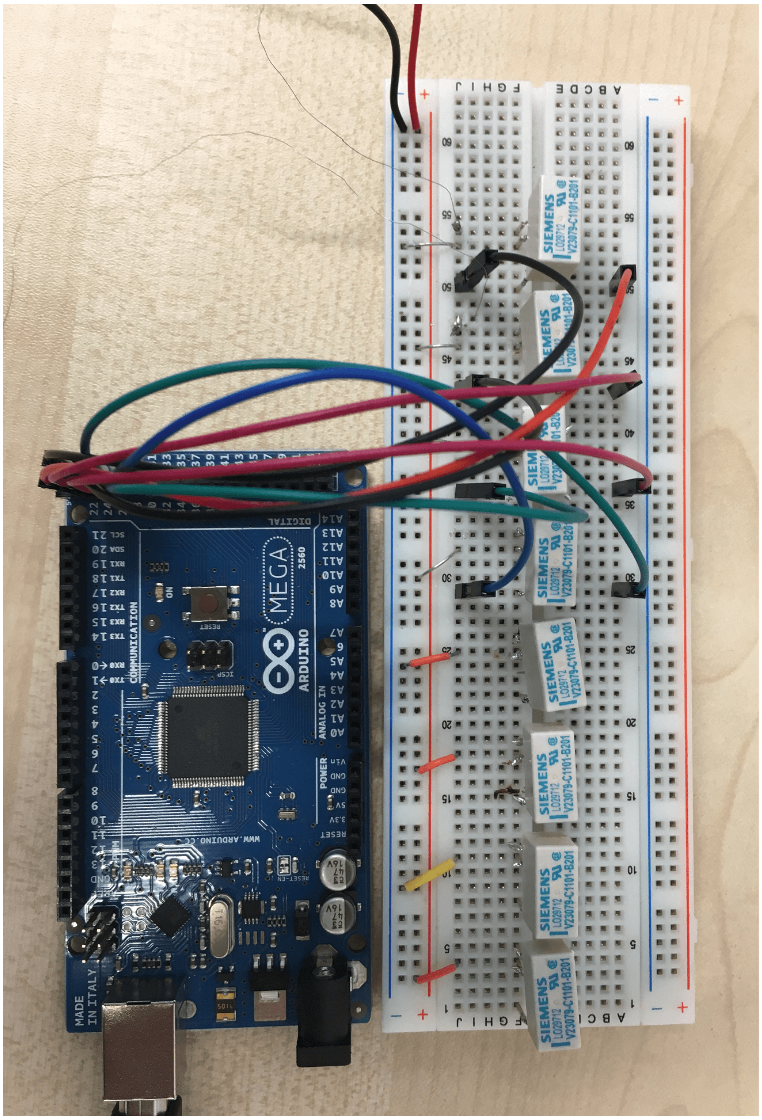

Figure 3.15: An electrical circuit realized on a breadboard with relay logic.

cal uses cases are, for example, to control systems, where more than one BMX is used. Usually these are either differential systems like DRAG bracelet or BRUSH prototype, or SNAKE kind of effect. This circuit consists of an array of relays, depending on how many BMX or BMX sub paths are used. The relays are used in pairs. Every single pair is responsible for controlling one BMX or one BMX sub path.

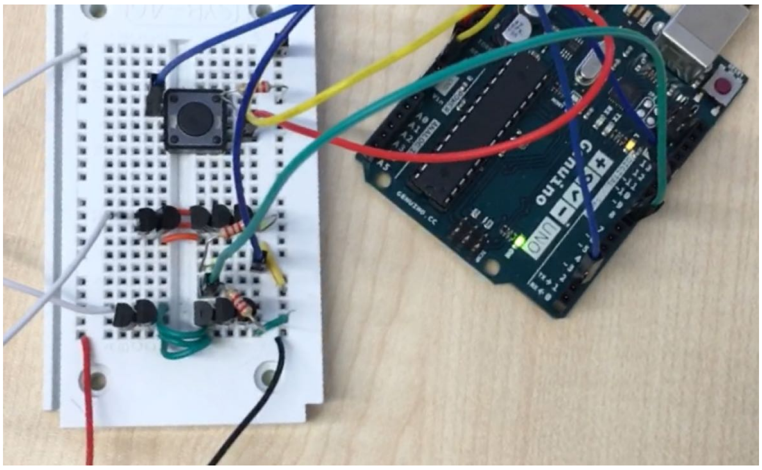

Figure 3.16: An electrical circuit realized on a breadboard with transistor logic.

Every single relay is responsible for activating either V+ or V-, so that another relay from the pair activates V- or V+ accordingly. Furthermore, every relay consists of a number of PINs. Two of those PINs are control PINs and they are connected to the corresponding Arduino PINs. If a high signal comes from Arduino to one of those PINs, the relay either connects V+ or V- PIN to the power supply, or disconnects it. In such a way one relay closes one part of the electrical circle. In order to fully close the electrical circuit, two relays in pair should be used. If one of them activates V+ and another one V-, then the circuit is closed and current is fed through BMX.

Fig.3.16 shows, how the second type of logic is implemented. For simplicity consider that a hardware button does not exist since it was then replaced by a software button from the GUI. The software button has no debouncing problems and is just better to control. The breadboard consists of two arrays of transistors, where each of them controls a single BMX. All transistors in one array are connected in parallel to equally divide current. If a high signal comes from Arduino to the transistor's base, then the emitter and the collector are connected to each other. In this case the electrical circuit is closed and current is fed through BMX.

Electrical circuit with transistor logic is able to control the speed of contraction using PWM, however it is quite tricky to use this logic in a scenario with multiple BMX.

Both types of logic have its advantages and disadvantages. Transistor logic can handle pulse width modulation (PWM) and in such a way use only one voltage supply to produce different levels of it. However it is not very flexible, if several BMX should be used. On the other hand, relay logic is able to work with multiple BMX, but struggles with the PWM mode, because relays are too slow in switching compared to transistors. Thus it depends on an application, which type of logic should be used.

GUI is implemented in *Processing* and allows to take full control over the haptic bracelets.

In order for a user to interact with haptic bracelets, the graphical user interface from Fig.3.14 was created. It was implemented using *Processing* programming language in junction with the transistor logic of the electrical circuit. The interface allows to take full control over the majority of bracelets. Differential systems can be simulated as well. Fig.3.17 shows how it looks like. Here you can specify, which BMX should be activated. Then, you can choose how many contractions should be made, specifying the contraction and relaxation times for one period. Furthermore, a fraction of voltage supply can be specified too.

For example, if a user is wearing PUSH bracelet from Fig.3.5 and he wants to make 3 consecutive pushes with the contraction time of 300 milliseconds and relaxation time of 5 seconds within one push, he should fill the GUI form like shown in Fig.3.17. Additionally the user specifies here that he wants to use $117/255 * U$ voltage supply. After all required data was put into the form, he pushes the software button *CONTRACT* and the bracelet is activated with the corresponding configuration.

Control parameters

For every haptic bracelet there exists a mapping of control parameters to what they actually influence:

Contraction path is influenced by the time, during which current is fed through BMX; Speed of contraction - by PWM; Contraction force - by a number of BMX put in parallel.

- Contraction time influences a certain distance BMX will make, while being contracted;
- Relaxation time influences a certain distance BMX will make, while being relaxed;
- Voltage supply influences the speed of contraction;
- Number of BMX put into one haptic bracelet influences the contraction force;

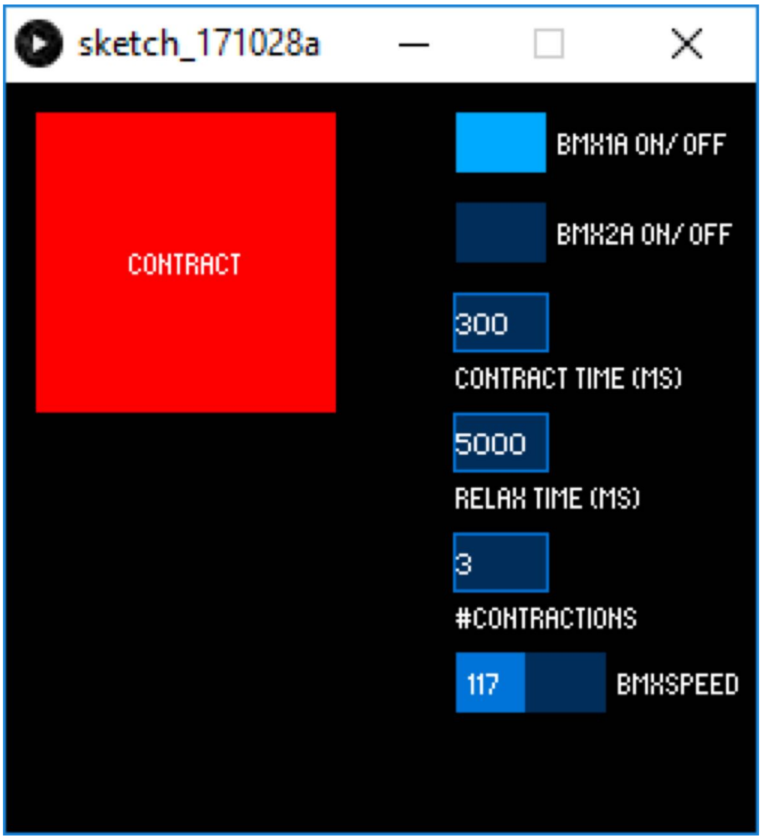

Figure 3.17: Graphical user interface to control haptic bracelets.

- Number of contractions influences the pattern.

To justify some of these mappings we conducted a small test, which results are shown in Tab.3.1 below. From this table you can see, that if contraction time is increased, then in all cases BMX makes longer distance, which proves validity of this mapping.
We then fix the contraction time at $100msec$ and compare what distance BMX made during this time for $9V$ and $12V$. In case of $9V$ BMX could make at maximum $11mm$, whereas in case of $12V$ BMX made $22mm$. It is obvious that the speed of contraction is bigger for $12V$. As the table shows, this is a general tendency, so voltage supply indeed influences the speed of contraction.
BMX is able to generate $30grams$ force, but it is quite obvi-

$U(Volts)/t_{contract}(msec)$	100	200	300	400	500	700	1000	2000
3	0.5	0.5	1-2	3	3	4-5	5-6	18
6	3-4	5-7	13	15	15			
9	5-11	22	22					
12	22							

Table 3.1: Distance in mm BMX makes, depending on voltage supply and time of contraction.

ous that if we double the amount of BMX, then the contraction force should double as well.

All mappings influence how a user actually perceives a haptic sensation on the skin and how comfortable it is. To answer both qualitative and quantitative questions and to justify all hypothesis, a user study was set up, which is described in the next section in more detail.

Chapter 4

Evaluation

After a set of haptic bracelets was created, we then conducted a user study to evaluate their characteristics. The primary goal is to determine what haptic sensations on the skin participants perceive while wearing different haptic devices in form of bracelets. Their response should help to improve these bracelets to be more effective and comfortable.
We conducted the first informal study with one research assistant to establish a future process. A number of haptic bracelets was randomly chosen to be tested. While testing them on the assistant's wrist, few of them indicated known issues regarding the heat problem. As a consequence, these bracelets were redesigned taking into consideration the proposed solution to the heat problem.

4.1 User study on sensations created from haptic bracelets

After none of the bracelets had shown any issues, we conducted the user study. There are in total four independent variables that influence this study:

- PROTOTYPE = {*1,..,6*};
- NUMBER OF BMX = {*1,2*};
- VOLTAGE SUPPLY = {*9V, 12V*};
- ADDITIONAL INFORMATION = {*true, false*}.

PROTOTYPE mapping looks as follows: *1*: PUSH, *2*: ROLL, *3*: TAP, *4*: PINCH, *5*: SCRATCH, *6*: DRAG. NUMBER OF BMX variable is responsible to determine, how many actuators are placed into a particular prototype. VOLTAGE SUPPLY variable is responsible to set specific amount of current flowing through the BMX(s). At last, ADDITIONAL INFORMATION variable determines whether or not the participants were shown beforehand, how all prototypes look like, as well as, what sensations they deliver when worn on the participants' wrist.

User study characteristics: 4 independent variables; 5 participants with and without prior experience with tactile feedback on the skin; 24 experiments for each participant; 6 demonstrators; randomized order.

If we exclude the last independent variable from a total number of experiments, we obtain twenty-four experiments for each participant. All twenty-four experiments are divided into two blocks, each consists of twelve experiments. The first block uses one BMX in all its prototypes, whereas the second block uses two. Furthermore, each block is divided into two sub blocks, each consists of six experiments. The first sub block uses 9V voltage supply for all its prototypes, whereas the second sub block uses 12V. Thus, a single experiment represents wearing one specific prototype that uses either one or two BMX(s), and an electrical circuit uses either 9V or 12V voltage supply.

Participants
Five volunteers participated (two women), age 22-29 years old (average 25.8). Four participants have their right arm as dominant. Two participants have prior experience with tactile feedback on the skin. Now the presenation order of experiments for each participant can be encoded into a Tab.4.1 .

Procedure
First, a participant is informed about the goal of the study. Then, depending on whether or not he belongs to a group of those who get additional information, he either first

User ID	Block 1	Block 2	Block 3	Block 4
1	BMX1-9V-123456	BMX1-12V-135246	BMX2-9V-246135	BMX2-12V-654321
2	BMX2-9V-123456	BMX2-12V-135246	BMX1-9V-246135	BMX1-12V-654321
3	BMX1-12V-123456	BMX1-9V-135246	BMX2-12V-246135	BMX2-9V-654321
4	BMX2-12V-123456	BMX2-9V-135246	BMX1-12V-246135	BMX1-9V-654321
5	BMX1-9V-123456	BMX1-12V-135246	BMX2-12V-246135	BMX2-9V-654321

Table 4.1: The presentation order of experiments for each participant.

takes a glance into how bracelets work and signs the consent form, or directly signs the consent form.
The participant sits in a chair in front of a table. There is a construction placed on the table with a hole to allow the participant put his dominant arm into it. The whole construction is covered with a textile piece to prevent potential guessing of what haptic sensation is going to be provided. In addition, the participant is asked to wear noise cancellation headphones. Then, depending on a position from the matrix in Tab.4.1 , a particular bracelet is worn on the participant's wrist with an appropriate number of BMX(s) and voltage supply. A time interval, during which the electrical circuit is closed, is set. After the setup is done, the bracelet is triggered by sending several Bytes over the COM port of Arduino microcontroller. This is done three times in a row to give the participant a chance to better qualify the sensation. The participant can ask for more repetitions. At last, a data collection step takes place and another iteration is done until ideally all twenty-four experiments have been covered. Fig.4.9 shows how the setup looks like.

Participants do not see which haptic bracelet is worn to prevent potential guessing. They also wear noise cancellation headphones to fully concentrate on sensations.

Data collection
For every experiment a participant is first asked to select from a list of nouns the one, which best described the sensation. We chose nouns based on known descriptions of haptic sensations on the skin: pinching, scratching, dragging, pushing, pulling, twisting, tickling, brushing, rolling, tapping. If the participant is unsure about the current sensation, he can put his own definition into the list. Afterwards, he should rate the characteristics of the haptic sensation on a 5-point Likert scale in terms of perceptibility and comfort, where *1* is the lowest level and *5* is the highest accordingly.

Participant's form: pick from a list of nouns the one, which best describes the sensation; rate from 1 to 5 how perceivable and comfortable the sensation was.

4.2 Results and discussion

As a next step after collecting the raw data was to evaluate them and compare results with the expectation. For this purpose six metrics were found:

- Probability distribution of how each prototype really feels like, if the participants did not know any additional information about the haptic bracelets;
- Probability distribution of how each prototype feels like, if the participants did get additional information about the bracelets;
- Statistics of which combination of conditions *BMX(s)/Voltage* was the most perceivable;
- Statistics of which combination of conditions *BMX(s)/Voltage* was the most comfortable;
- Statistics of which bracelet was the most perceivable;
- Statistics of which bracelet was the most comfortable.

All values were calculated by using frequential analysis of the raw data.

How PUSH bracelet feels like
Fig.4.1 shows two probability distributions of how PUSH bracelet feels like, if the participants did get (blue) and did not get (orange) additional information about it.

If PUSH bracelet is worn, then in 30% cases the pushing sensation is felt, followed by the tapping sensation in 28% cases.

The first thing to notice is that in case the participants did not get additional information, they mixed up PUSH sensation with way more other sensations, than in case if they did get information. If the participants did get additional information, they were pretty sure (42,9%) cases that PUSH was indeed PUSH sensation. In 28,6% cases the participants mixed PUSH with TAP sensation, which is a pretty common tendency. This statement is proven by the fact, that if the participants did not get additional information, they were likely (27,3%) to say that PUSH feels like TAP, followed by PUSH (18,2%) sensation.

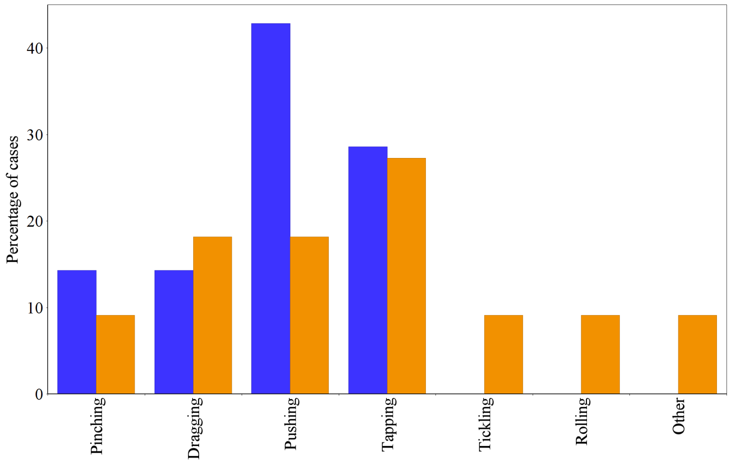

Figure 4.1: Statistics of how PUSH prototype feels like if shown (blue) and not shown (orange) to the participants beforehand.

If we build an average between two probability distributions and take two most probable results, then we would get the following outcome. If PUSH bracelet is worn, then in 30% cases the pushing sensation is felt, followed by the tapping sensation in 28% cases.

How ROLL bracelet feels like
Fig.4.2 shows two probability distributions of how ROLL bracelet feels like, if the participants did get (blue) and did not get (orange) additional information about it.
Here the participants who did not get additional information mixed up ROLL sensation with way less other sensations, than in the case with PUSH under the same condition. If the participants did get additional information, they were totally sure (100%) that ROLL was indeed ROLL sensation. Also the participants, who did not have information about the bracelet, in most cases (55,6%) could correctly interpret ROLL sensation.

If ROLL bracelet is worn, then in 78% cases the rolling sensation is felt.

If we build an average between two probability distributions and take the most probable result, then we would get the following outcome. If ROLL bracelet is worn, then in 78% cases the rolling sensation is felt.

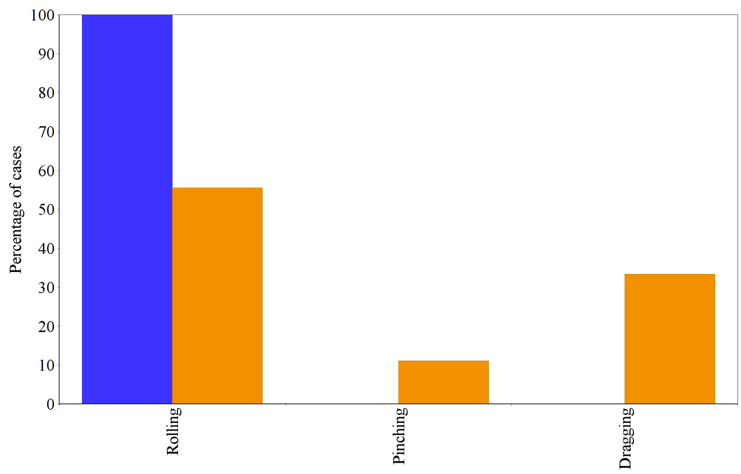

Figure 4.2: Statistics of how ROLL prototype feels like if shown (blue) and not shown (orange) to the participants beforehand.

How TAP bracelet feels like

Fig.4.3 shows two probability distributions of how TAP bracelet feels like, if the participants did get (blue) and did not get (orange) additional information about it.

If TAP bracelet is worn, then in 56% cases the tapping sensation is felt, followed by the pushing sensation in 27% cases.

A noticeable thing here is that the participants with prior knowledge about the TAP bracelet still mixed up TAP with PUSH sensation in some cases (14,3%). However they were pretty sure (71,4%) that TAP was indeed TAP sensation. On the other hand, the participants without prior knowledge about the bracelet struggled to differentiate between TAP (40%) and PUSH (40%) sensations, which again proves the statement above.

If we build an average between two probability distributions and take two most probable results, then we would get the following outcome. If TAP bracelet is worn, then in 56% cases the tapping sensation is felt, followed by the pushing sensation in 27% cases.

How PINCH bracelet feels like

Fig.4.4 shows two probability distributions of how PINCH bracelet feels like, if the participants did get (blue) and did not get (orange) additional information about it.

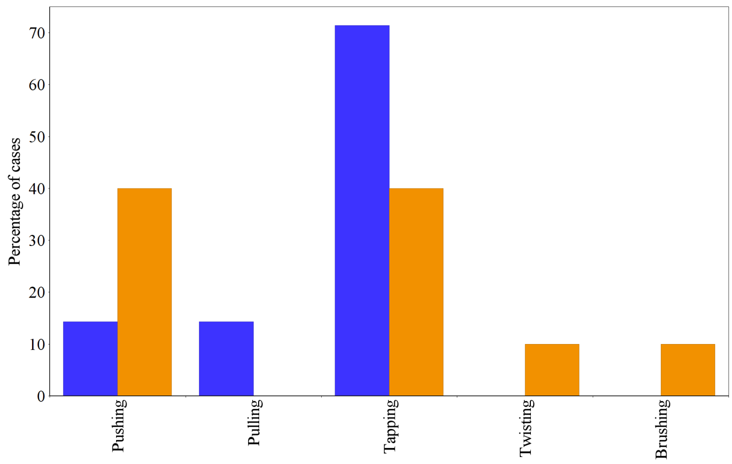

Figure 4.3: Statistics of how TAP prototype feels like if shown (blue) and not shown (orange) to the participants beforehand.

In this case regardless of whether or not the participants had additional information, they were pretty sure it was a unique sensation on their skin. The way, how both probability distributions look like, speaks for this fact. However the participants with prior knowledge of the bracelet were totally sure (100%) that PINCH was indeed PINCH sensation. Unlike them, the participants who did not get additional information rated PINCH as PULL sensation in most cases (62,5%). Only in 25% they guessed correctly that PINCH was indeed PINCH sensation.

If PINCH bracelet is worn, then in 63% cases the pinching sensation is felt, followed by the pulling sensation in 31% cases.

If we build an average between two probability distributions and take two most probable results, then we would get the following outcome. If PINCH bracelet is worn, then in 63% cases the pinching sensation is felt, followed by the pulling sensation in 31% cases.

How SCRATCH bracelet feels like

Fig.4.5 shows two probability distributions of how SCRATCH bracelet feels like, if the participants did get (blue) and did not get (orange) additional information about it.

If SCRATCH bracelet is worn, then in 56% cases the scratching sensation is felt.

The participants with prior knowledge of the bracelet were

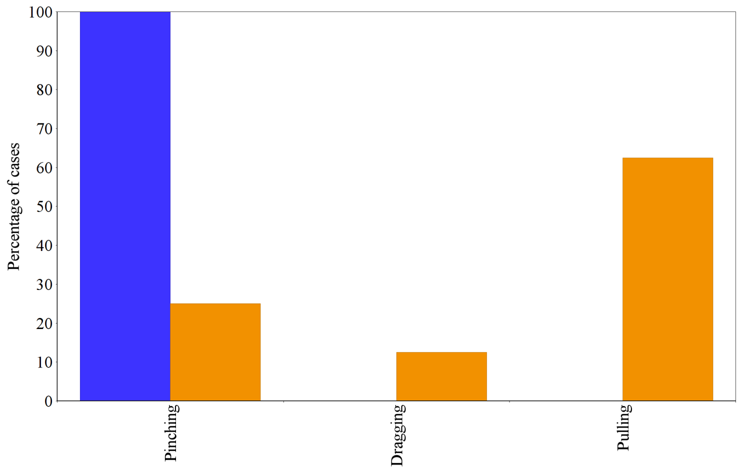

Figure 4.4: Statistics of how PINCH prototype feels like if shown (blue) and not shown (orange) to the participants beforehand.

66,7% sure that SCRATCH was indeed SCRATCH sensation, followed by 33,3%, where they thought SCRATCH was BRUSH sensation instead. The participants without prior knowledge could correctly pick the right answer in 45,5% cases.
If we build an average between two probability distributions and take the most probable result, then we would get the following outcome. If SCRATCH bracelet is worn, then in 56% cases the scratching sensation is felt.

How DRAG bracelet feels like
Fig.4.6 shows two probability distributions of how DRAG bracelet feels like, if the participants did get (blue) and did not get (orange) additional information about it.

If DRAG bracelet is worn, then in 50% cases the dragging sensation is felt.

With this bracelet the participants who did get additional information were 100% sure that DRAG was indeed DRAG sensation, whereas those participants without prior knowledge could not find the right answer and struggled between picking PINCH (33,3%), or BRUSH (33,3%) or ROLL (33,3%) sensation.
If we build an average between two probability distributions and take the most probable result, then we would get

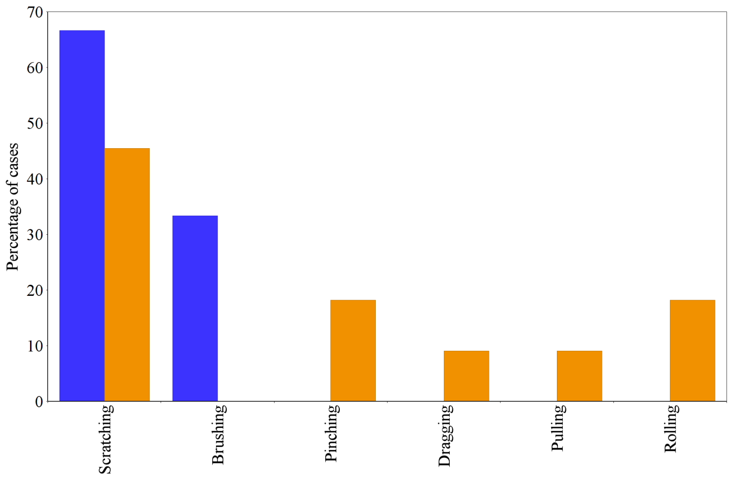

Figure 4.5: Statistics of how SCRATCH prototype feels like if shown (blue) and not shown (orange) to the participants beforehand.

the following outcome. If DRAG bracelet is worn, then in 50% cases the dragging sensation is felt.

Perceptibility of haptic bracelets and comfort of sensations they deliver

Fig.4.7 shows two important statistics at the same time, which is how perceivable (blue) and comfortable (orange) each bracelet is, regardless of a combination of conditions. It can be clearly seen that regarding perceptibility there are two clusters with three bracelets in each of them. The first cluster shows rather low level of perception (2,9 on average), where ROLL is the least perceivable among all sensations (2,8). The second cluster shows relatively high level of perception (4,2 on average). It consists of such bracelets as PINCH, SCRATCH and DRAG, where SCRATCH is the most perceivable among all sensations (4,5).

Least perceivable sensation - ROLL (2,8); Most perceivable - SCRATCH (4,5).

Regarding comfort of sensations we can see that those bracelets with low level of perception have actually high level of comfort (3,6 on average), whereas those ones with high perceptibility tend to show lower comfort. From Fig.4.7 we can spot two interesting samples. SCRATCH bracelet has the highest perceptibility, however the lowest

Least comfortable sensation - SCRATCH (2); Most comfortable - PINCH (3,9).

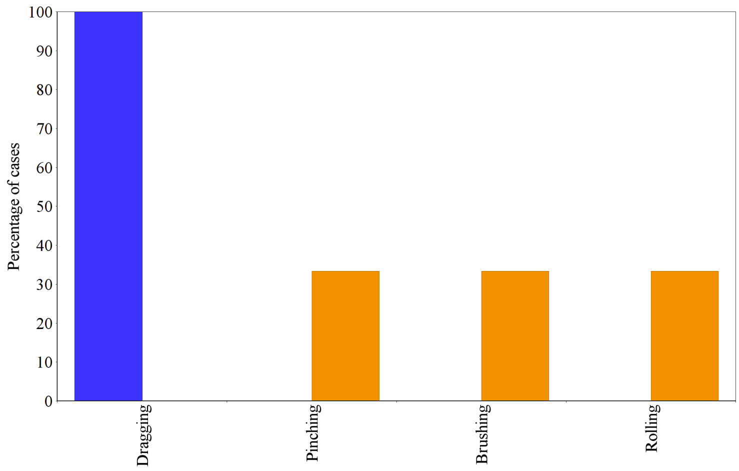

Figure 4.6: Statistics of how DRAG prototype feels like if shown (blue) and not shown (orange) to the participants beforehand.

comfort at the same time (2). The participants did not like this sensation, because it was rather unpleasant, however they noticed that in case this bracelet was used to indicate some important notification, it would be reasonable to use it. The second interesting sample is PINCH bracelet, which has the highest comfort (3,9) in terms of sensation on the skin, but shows the second highest level of perception (4,2) at the same time.

Perceptibility and comfort of a combination of conditions
Fig.4.8 shows another two important statistics at the same time, which is how perceivable (blue) and comfortable (orange) each combination of conditions is, regardless of bracelets. If we look at perceptibility aspect, we can see that it is an ascending order, where a combination BMX1/9V has the lowest level of perception (2,9) and BMX2/12V shows the highest level (3,5) accordingly. This was quite an expected result, however the difference in perception between all combinations is not very high. Looking at how comfortable each combination of conditions is, we can spot that there is only one outlier BMX2/12V with the least level of comfort (2,7). This was also an expected outcome since

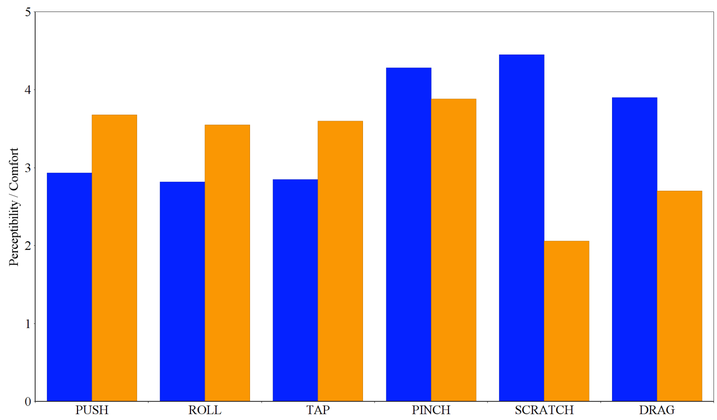

Figure 4.7: Ratings of perceptibility (blue) and comfort (orange) depending on a prototype, which is independent from a combination of conditions.

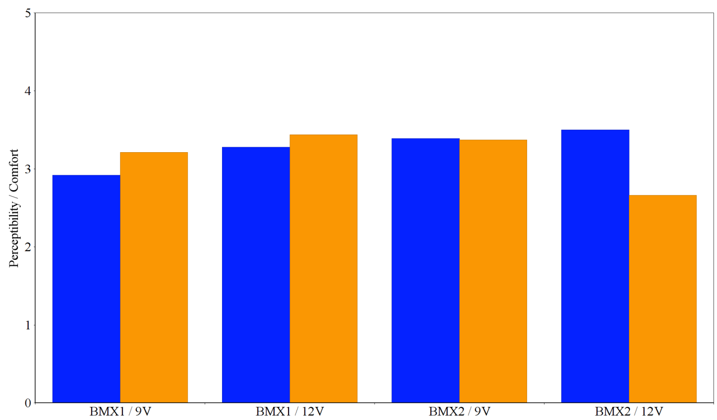

Figure 4.8: Ratings of perceptibility (blue) and comfort (orange) depending on a combination of conditions, which is independent from prototypes.

this combination is rather extreme.

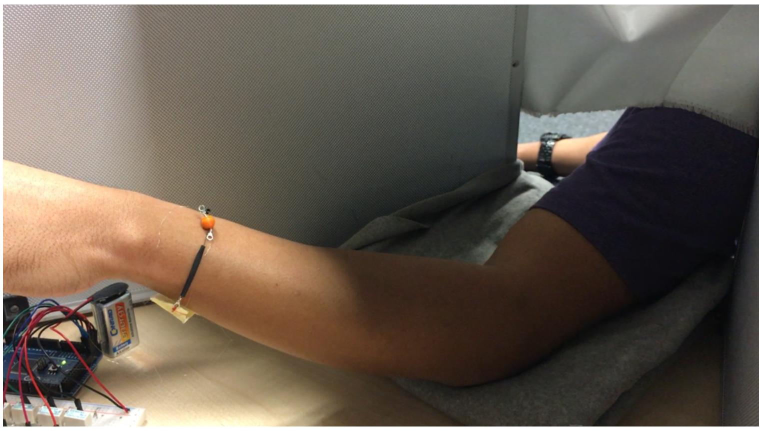

Figure 4.9: The setup for the user study.

4.3 Conclusion and reasoning

After the raw data was analyzed and put together, some conclusions can be made.
In general the participants, who did get additional information, could correctly guess the right sensation for each bracelet with a great level of certainty. On the other hand, the participants without prior knowledge of bracelets picked the right sensation only for three bracelets with lower level of certainty than before.
The participants tend to mix up two haptic sensations PUSH and TAP. A possible reason would be that these two bracelets share one assembly component, a so called stick, which interacts with the skin. In case of PUSH bracelet this stick has small area that touches the skin, and in case of TAP, this stick was not made long enough. In both cases the participants feel rather very localized sensation. Moreover, if a parameter that is responsible for how long the electrical circuit is closed, was set higher than necessary for TAP bracelet, then this leads to a more pushy effect on the skin.
The participants, who did not get additional information, mixed up PINCH with PULL sensation. A possible reason for this misinterpretation would be that these two effects are actually quite similar. The difference is that PULL can be seen as an enhanced version of PINCH sensation.
PINCH and DRAG bracelets look like they have a lot of po-

tential in terms of perceptibility and comfort and should be definitely explored further.
Overall, the majority of results from the user study are aligned with the expectations prior to the user study.

Chapter 5

Summary and future work

5.1 Summary and contributions

In this thesis we created a number of thin, lightweight, flexible, wrist-worn tactile devices. Usually the overall size of a haptic device depends on what type of actuator is used. To fulfil the requirements of a wearable tactile device from Chapter 3 we decided to use alternative type of actuators based on smart materials.
We then introduced a list of currently most popular smart materials that can be controlled either by magnetic or electric field. We compared them and came to conclusion that shape-memory-alloy BMX spring is the best choice to use it as an actuator. It is compact, lightweight, flexible and can produce good contraction force and good range of motion. One limitation with BMX actuator is that it heats to high temperatures, when current is fed through it. Since we wanted to build compact haptic devices, it was important to use it close to the skin. To avoid accidental contact and to let BMX cool faster to produce higher responses, we used two cooling techniques based on both convection and conduction cooling. In all our haptic bracelets we use air gap between BMX and the skin to create natural air flow and let it cool fast. We also either connect BMX to

heatsinks/terminals or partially package it into a tube to transfer heat from BMX to a cooler part.
Another BMX limitation is that it produces linear range of motion, so without providing additional measures it is possible to create only weak haptic vocabulary. We wanted to create rather reach vocabulary, so to overcome this limitation we use this linear motion of BMX to trigger moving physical structures in a more complex way. We built eight haptic prototypes to invoke eight different tactile sensations on the skin. They consisted of an assembly of 3D-printed physical structures that are moved using BMX actuator.
After designing our tactile bracelets we wanted to be able to control them. For this the corresponding hardware was chosen and merged together into a control system, which consists of a GUI implemented in *Processing*, Arduino program, electrical circuit and an actual bracelet. We describe the hardware and the whole system in details to facilitate replicating this work.
We evaluated the parameters that can be used to control the force of contraction, speed of contraction and path of BMX. We found that force of contraction is influenced by a number of BMX put in parallel into one haptic bracelet. Speed of contraction is influenced by the amount of current flowing through BMX, which is regulated by PWM mode. Finally contraction path is influenced by the time, during which current is fed through BMX.
To validate what haptic sensations on the skin users perceive while wearing different haptic bracelets, a user study was conducted. Results show that participants could not distinguish very well between pushing and tapping sensation. However by improving the corresponding bracelets as suggested in Chapter 4 the results should be better. Also pinching was someties mixed up with pulling sensation, but it is because the last one is an enhanced version of pinching. Other sensations could be interpreted much better. Overall, by improving the haptic bracelets and after some training, users should be able to distinguish different sensations much better.
During the user study we also found out two bracelets with good perceptibility/comfort ratio, which are PINCH and DRAG prototypes.
Overall results show that BMX actuators can generate

enough force and motion to move physical structures in a way that the skin can sense different tactile modalities.

5.2 Future work

Some other aspects were not in scope of this thesis and thus were deligated into the future work.
First of all, five haptic bracelets that were tested on the skin, should be improved. Their overall size can be decreased which would make them even more lightweight and compact.
PINCH sticker should transition from being a sticker to become an actual bracelet by creating physical context that would make attachments to the skin.
BRUSH and STRETCH prototypes should be tested on the skin. It looks promising to explore the DRAG idea in context of stretching the skin. As discussed in Chapter 3 , if we made a dragging element of different texture, flat and of bigger area, it would then be possible to stretch the skin while moving back-and-forth.
Great potential of perceptibility of our haptic bracelets depends on the quality of 3D-printer that prints parts of physical structures. Printing them on a high-standard 3D-printer would allow not only to print a whole assembly in one hop with a better quality, but it would also be possible to specify either the printing material should be flexible, or not, and everything in between. For example, ROLL and SCRATCH bracelets partially consist of some flexible parts to simulate desired sensations that were not 3D-printed. However if we could 3D-print them instead, this would not only lead to a better looking prototype, but also the overall perfomance would be better. Also, if the dragging element in DRAG bracelet was 3D-printed using some rubber material, then it would be possible to grab the skin and stretch it while moving.
At the moment DRAG bracelet can produce 1D motion with one pair of BMX. However if we used two pairs of BMX, it would be possible to create 2D motion in order to create more complex motion and thus encode more information. We could also attach one end of each BMX not to the wrist band, but to a spring instead, which would prob-

ably result in a greater range of motion.

We should make use of the discovered new BMX property, which allows not only to contract the whole BMX, but also sub parts of it. A corresponding haptic device should be designed to explore possibilities in creating different spatio-temporal patterns.

Generally, we should design a bracelet form factor to package our haptic prototypes and make them robust against some unexpected motions etc.

We also want to explore new tactile modalities that have not been covered in wearables research yet.

Finally, we want to create patterns to encode as much information as possible.

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