FEEL THE DIFFERENCE

Designing affective haptic wearables: Comparing shape memory alloy and electromechanical actuation

Master thesis - Tanja Overbeek

Master thesis

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April 2025
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Acknowledgements

I greatly enjoyed working on the project and creating this project, however, that would not have been possible without the help of many people. To these people, I would like to express my gratitude.

First, I want to thank my supervisors, Sepideh and Gijs. You have provided me with very meaningful guidance, without which I would have gotten stuck many times. I want to thank Sepideh for her enthusiasm, causing me to never lose interest in the project. You always provided suggestions that inspired me to explore new avenues and find new solutions. Additionally, your vast knowledge about materials and your ability to provide literature about anything I couldn't figure out helped me out more than a few times throughout the project. Secondly, Gijs helped me think about the bigger picture. Whilst I tend to focus on the technical details, you made sure I didn't forget about the human aspect of the project. You always provided feedback highlighting angles and aspects of the project I did not even think about yet.

Next, I want to thank all the participants who helped me by enduring my user tests. I have scoured all my friends and family members to participate. Thank you for providing me with enjoyable company when fun no longer came entirely by itself.
I want to thank my family, Monica, Lucas, and Julia, for listening to my troubles when I got stuck, and for their feedback that helped me move forward again. I want to thank Gina, Belle, Kim, and Fleur for studying together with me at the university and for the many coffees together to break the day. Thank you to my roommates for chatting after a long day of work, helping me to leave the work at university and be able to relax at home. Finally, I wish to thank my friends from high school, from my Hydro Motion team and my association friends for their continuous support and encouragement throughout the project.

I was afraid that my graduation project was going to be brutal, but thanks to all these people, I really enjoyed it. Many thanks to all of you!

Executive summary

In daily life, a lot of information is transferred though the various sensory channels. In particular, the sense of touch can play a versatile role, introducing the field of haptics. There is still much to explore and research to be done regarding haptic feedback. This project specifically looked into the actuation method for haptic wearables, comparing the influence of shape memory alloy (SMA) and electromechanical actuation.

Through a literature review, the field of affective haptics became the focus of the project, applying cutaneous haptic wearables on the forearm to influence the emotions of the user. Additionally, evaluation metrics relevant to haptic wearables were determined. Two sensations were selected to explore the influence of the actuation method on the design process of the designer as well as the user experience of the user: a short, intense squeezing sensation opposing a long, soft stroking sensation. Using either actuation method a haptic wearable was designed for each sensation, resulting in four devices. Using these devices, user tests have been conducted.

The insights gathered during the project showed that electromechanical actuation is more suitable in several situations, and SMA actuation in other. Mechanical actuation needs to be used if a sensation using high frequency repetition needs to be created, whilst SMA actuation is more suitable when several sensations in close proximity are desired. When creating a big displacement along lengths, mechanical actuation is needed, however, when following the curves of the human body, SMA actuation should be used. Mechanical actuation can provide precise control over the movement, while SMA actuation provides simpler, more intuitive control over the final movement. When looking at key metrics, mechanical actuation can provide noticeable differences in speed, and SMA actuation noticeable differences in force. The user experience of SMA actuation is pleasant and humanlike, providing a sense of comfort; whilst mechanical actuation is experienced as intense and creates a sense of urgency in the user. As a conclusion to this project, these results were gathered and summarized into a decision flowchart.

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Introduction

In today's fast-paced world, a lot of information is constantly being transferred. Noticing the people around you to walk along the busy street without collisions, the sound of the notifications on your phone or feeling if an avocado has ripened. All this information is transferred to you through different channels, through the various senses of humans.

The sense of touch is very versatile and therefore offers many opportunities, bringing the world of haptics comes into play. Haptics refers to the sense of touch, the primary means for people to interact with their environment; to feel textures, receive a reassuring touch or even touch the digital world. Since touch is such a versatile sense, a great deal of research has been done into haptics, yet there is still so much to explore. Especially, as we live in an increasingly digital world where haptic devices can enhance the interaction between humans and devices. When able to produce realistic and effective haptic feedback, the digital experience can be greatly improved. To work towards this, more research is still necessary, and this project looks into the action method, as this is still a key limitation of haptic wearables (O'Malley & Gupta, 2008).

There are haptic wearable designs using various classic actuation methods, such as stepper and servo motors (Pacchierotti et al., 2017). Yet, there are also wearables designed that use Shape Memory Alloy (SMA) as actuation (Hamdan et al., 2019). From these designs, it becomes very clear that both actuation methods have great advantages and various suitable applications. SMA is known for its compactness and as a lightweight solution (Liu et al., 2023), while on the other hand, conventional electromechanical actuation provides robustness and controlled motion (Dunkelberger et al., 2018).

While both actuation methods have proven themselves in individual applications, a systematic comparison is currently lacking. Such a comparison is essential, as the choice of actuator greatly influences not only the performance, but also the wearability, responsiveness, and user experience of the device. When working in the field of haptics, trade-offs between factors like size, speed, controllability, and comfort are often faced, yet there is limited practical guidance available to support these decisions. With haptic feedback increasingly being used in medical rehabilitation, assistive technology, virtual and augmented reality, and other human-computer interaction domains, understanding how different actuation methods shape user experience becomes crucial.

This project aims to generate insights for designers, providing guidance on when SMAs can be a valuable material and when to rely on conventional electromechanical actuation for creating haptic wearables. To explore how different actuation methods influence the user experience of haptic wearables, this project selected two opposing sensations. By approaching these through both Shape Memory Alloy actuation and electromechanical actuation, the project investigates how the choice of actuation method influences both the design and user experience of a haptic wearable. By exploring both the performance side as well as how the device is perceived, the aim is to provide a clearer understanding of which actuation method best suits different interaction goals.

This report is structured as follows. It begins with a literature review on haptics, Shape Memory Alloys, electromechanical actuation, and relevant evaluation metrics. The subsequent section outlines the design process and presents the final wearable prototypes. This is followed by a user evaluation, detailing the test setup and results. The design experience is then reflected upon, highlighting specifications of the wearables and key insights from development. Finally, the discussion addresses the interpretations, implications, limitations, and opportunities for future work, before the conclusion with a comparison of the two actuation methods is presented.

Research phase

Haptics

Haptics makes use of the sense of touch, which can be split into active and passive touch. Active touch is used to explore the world around us, feeling for example shapes, materials and stickiness (Lederman & Klatzky, 2009). In contrast to passive touch, which refers to being touched (see Figure 1). When this is done by a device, this is also called haptic feedback (Lederman & Klatzky, 2009). Since the sense of touch can be described as multidimensional (See et al., 2022), there are many opportunities found regarding the application, type of haptic feedback used, how the device is used and more.

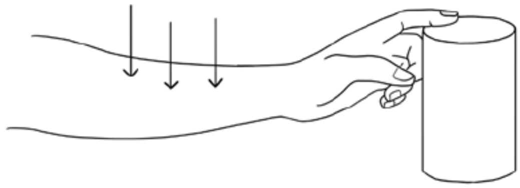


Figure 1 - Active and passive touch

Haptic perception

When working with haptics, the perception of the user is very important. It is therefore necessary to understand how haptic feedback is felt and how it is perceived by the user.

The sense of touch can be split into two: cutaneous and kinaesthetic touch (O'Malley & Gupta, 2008). Cutaneous feedback enables feeling texture, temperature, and pressure when interacting with an object. Kinaesthetic feedback refers to the weight, movement, and position of the object (Emami et al., 2024). In Figure 2, this is visualized, the texture of the ball is felt through cutaneous touch whilst the weight is experienced through kinaesthetic touch. This is felt through mechano- and thermal receptors embedded in the skin and mechanoreceptors found in the muscles and joints. The receptors in your skin are responsible for the cutaneous feedback, and those in your muscles and joints for the kinaesthetic feedback (Lederman & Klatzky, 2009).

Cutaneous touch is the focus of this project, meaning that the receptors found in the skin are the ones that will be experiencing the sensations created by the devices. While a lot of information can be gathered through cutaneous touch, the ability to do so varies across different parts of the body. This is due to the density of mechanoreceptors, which differs per area. As a result, differences occur in the sensitivity, acuity and magnitude of tactile and thermal sensations (Lucker, 2023). It is important to take these differences into account when working with haptic feedback, as this will influence the details that can be interpreted.

The Just Notable Difference (JND) is a way to quantify the sensitivity f human senses (Barontini, 2025). JND is the smallest measurement needed between two signals to ensure that they can be perceived separately. For haptics specifically, the two-point touch threshold or 2-point discrimination (2PD) is commonly used. In Figure 3, this threshold is visualized for the areas across the body. Several studies are displayed in the figure, each showing big differences across the body (Mancini et al., 2014). The fingertips are the most sensitive, followed closely by the palm and forearm. Figure 4 shows a body map of impedance, visualizing where wearables can be placed based on how much a device could hinder the user when worn. When combining these two figures, the forearm would be a suitable location for a haptic wearable.

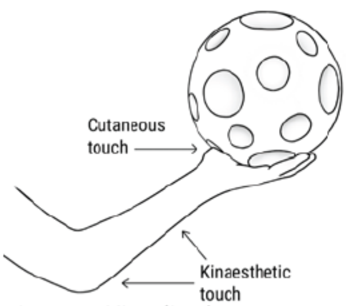


Figure 2 - Visualized cutaneous and kinaesthetic touch

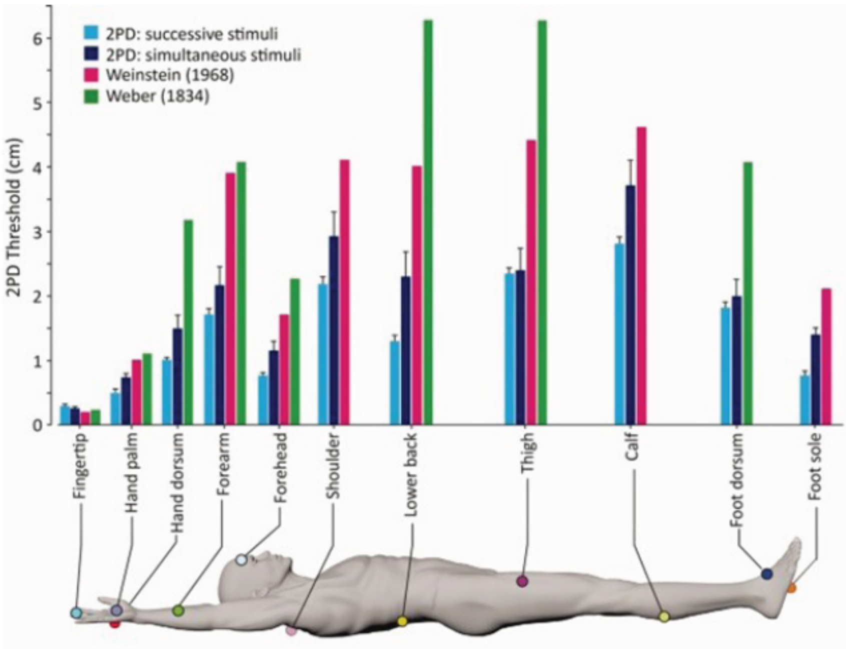


Figure 3 - Two-point touch threshold across the body (Mancini et al., 2014)

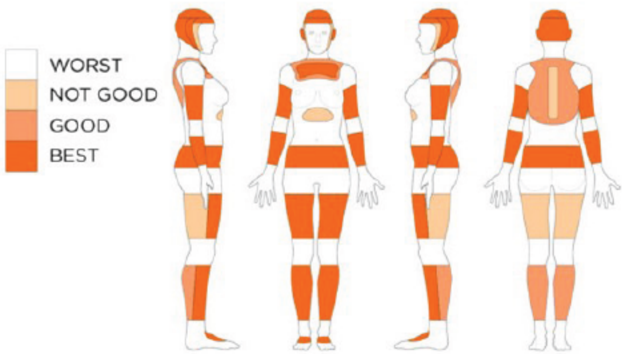


Figure 4 - Impedance body map (Zeagler, 2017)

Haptic feedback

Haptic feedback refers to the sensations produced by a device. The type of haptic feedback used can significantly influence the experienced sensation.

Considering that the sense of touch is quite diverse, several types of haptic feedback can be used. The main types of cutaneous haptic feedback are vibrotactile, skin-stretch, compression, thermal, and electrical feedback (Adilkhanov et al., 2022).

Providing haptic feedback by using vibrations is now frequently used in, for example, phones. While many different vibration patterns can be used, the meaning of the pattern often varies between devices as well as the interpretation of the user; whereas skin-stretch feedback could provide easier to interpret information to the user. Similarly to vibration patterns, there are still a lot of choices to be made regarding, for example, speed and force that will influence the sensation of the haptic feedback

Haptic device types

A device providing haptic feedback to a user naturally needs to be in contact with this user. There are three common ways to achieve this. The categories in which haptic feedback devices generally can be divided in are grounded devices, hand-held devices, and wearable devices (see Figure 5) (Adilkhanov et al., 2022). For this project, the focus is on wearable devices.

Wearable haptic feedback devices can be split again into two categories: body-grounded devices and cutaneous devices (Adilkhanov et al., 2022). A body-grounded device is grounded on the user themselves, meaning that the user will feel both the intended force and its counterforce. They are also often called exoskeletons and are mostly used to provide kinaesthetic haptic feedback. Technically these devices are wearable, however, they are often heavy and bulky and therefore not always comfortable. Cutaneous haptic feedback devices are used for providing cutaneous feedback, these are usually smaller and more wearable. For this research, the focus will be on wearable cutaneous haptic feedback devices.

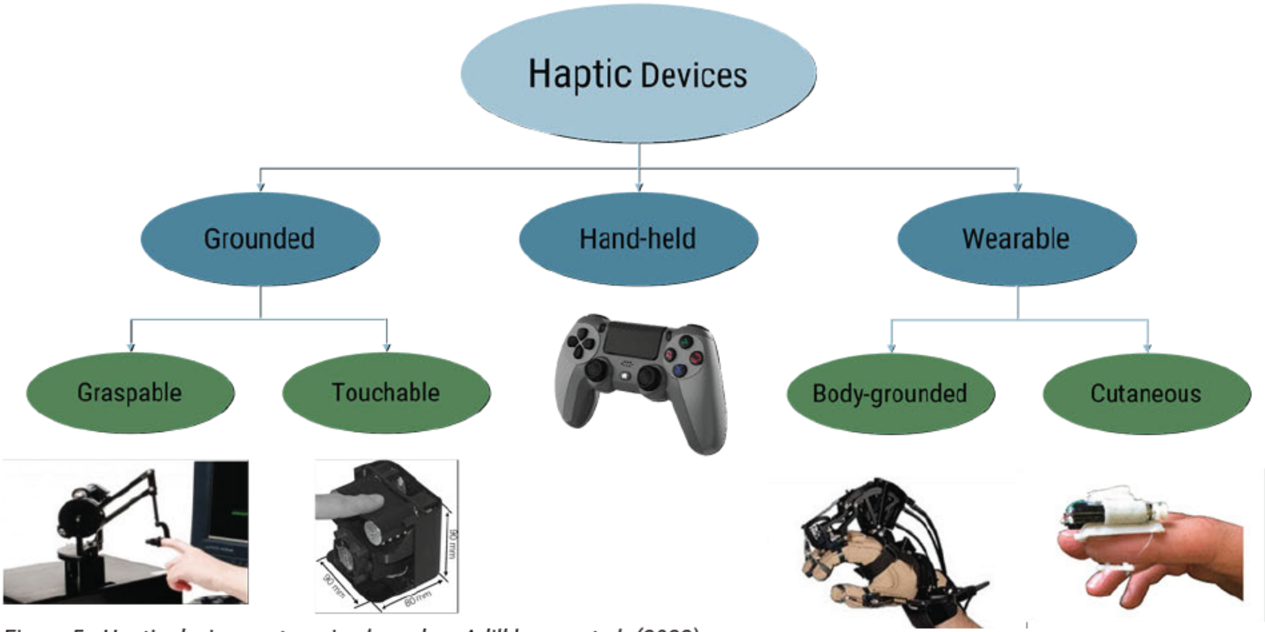


Figure 5 - Haptic devices categories based on Adilkhanov et al. (2022)

Haptic fields

When designing a haptic-feedback device, the specific application will influence a lot of th bles are often used: notification haptics, virtual- and augmented reality (VR/AR) haptics, and affective haptics (Liu et al., 2023).

Notification haptics is an application where the wearable device is used to convey information. This is often used in, for example, a mobile phone or a smartwatch. Different vibration patterns are used to convey different messages and are learnt by the user. However, more advanced haptic cues are also possible in notification haptics. For example, in a navigational device, a cue indicating left or right can be given using directional movement (Kuang et al., 2022).

The VR/AR haptics field is growing rapidly, in which haptics is applied to enhance the immersive experience. In the VR application, kinaesthetic haptic feedback is often used to mimic the touching of objects that appear in the virtual world. Additionally, there are simpler forms of haptics applied here, such as vibrations in the handheld controllers simulating the touch sensation.

In the field of affective haptics, the aim is to influence the emotional state of the user by, for example, recreating human touch. The user can be comforted by the touch of a loved one or calmed down by a haptic wearable recreating a breathing pattern in a stressful situation. When recreating human touch, a new layer of complexity is added in the haptic system (Huisman, 2017). Several aspects need to be considered, such as force and warmth, which all influence the interpretation and should be aligned perfectly to create the intended sensation. When influencing the emotional state of the user, the sensation must be considered carefully to ensure the desired intention is perceived.

For this project, the field of affective haptics will be the focus, specifically affective touch. This is because a lot more research has been done into task-oriented haptic devices, and less into affective haptics. This research field is becoming increasingly relevant to society, since there is a growing need for affective touch in the digitalising world (Raisamo et al., 2022).

Affective haptic devices

To understand how affective haptic devices can be applied, several devices will be discussed in the following section. The actuation, sensation and intended effect are of these devices are discussed.

In figure 6, the CUFF designed by Ghiasi et al. (2019) is shown. The CUFF is designed to enhance the emotional perception of texts, using two motors. The CUFF can squeeze the user, and create a caressing sensation. They conducted a user test in which they researched if the haptic feedback had an effect on the perception of the texts, comparing neutral and high arousal texts. Their results confirm that haptic feedback can certainly influence the users emotions.

Figure 6 – The CUFF

In Figure 7, the vibro-tactile wristband design by Tavana et al. (2024) is shown. This device is designed to convey the emotions happiness, sadness, anger, and relaxation using two vibration motors. They researched the ability to interpret a vibrational sensation and to understand the underlaying emotion. Their studied showed that vibrational haptic feedback can convey the emotions to the user, however, they do indicate that there are limitations to this. Happiness and anger were most clear to understand, however, their design was unable to convey sadness and relaxation clearly. This device shows how users can interpret haptic feedback and understand the conveyed emotion, but it also shows the limitations of vibrational feedback as well as the design of the device.

Figure 7 - Vibro-tactile wristband

In Figure 8, a wearable device emulating affective touch on the human forearm using linear actuator is shown, designed by Valle et al (2023). The device is designed to create a stroking motion along the arm. They designed the device to compare to already existing devices using voice coil motors and vibrotactile stimulation, researching if their device can provide more realist sensations. In their research paper they looked into different patterns of actuation, where the speed, indentation depth, and force can be varied. They discussed the benefits of their design, however, no user tests have been done to validate them.

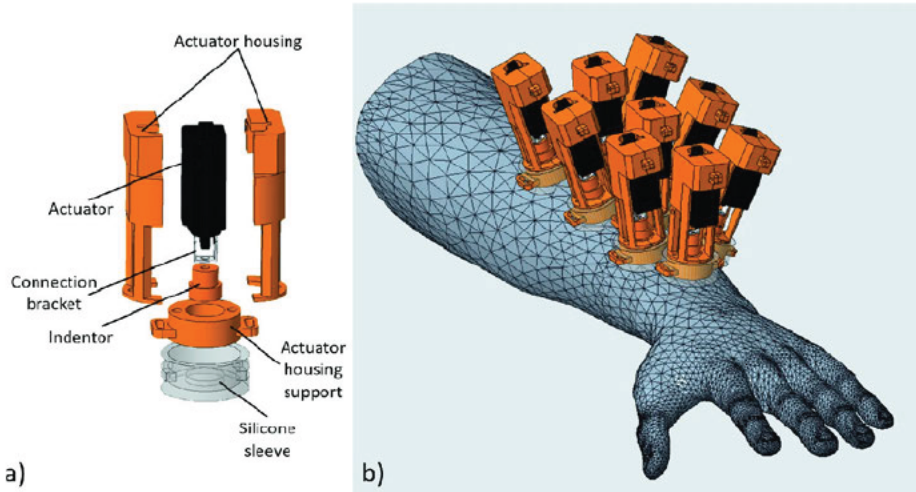


Figure 8 - Stroking device using linear actuators

In Figure 9, a SMA actuated garment is shown, designed by Foo et al. (2021). They conducted tests to gather user expectations in using varying 'warm touch' parameters to communicate 7 distinct emotions. They concluded that a 'universal warm touch recipe' for communicating emotions might not be possible. Indicating that when designing a haptic wearable, flexibility for interpretation differences per user should be taken into account by limiting the conveyed message options.

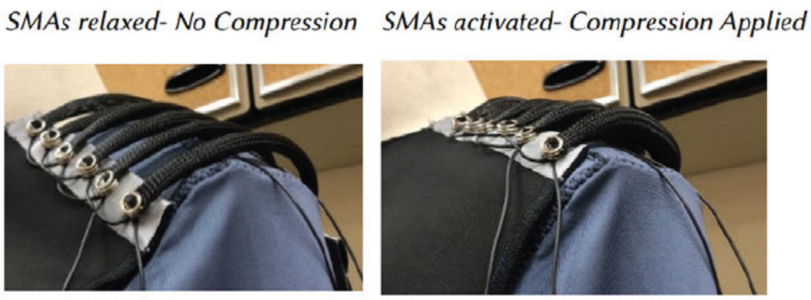
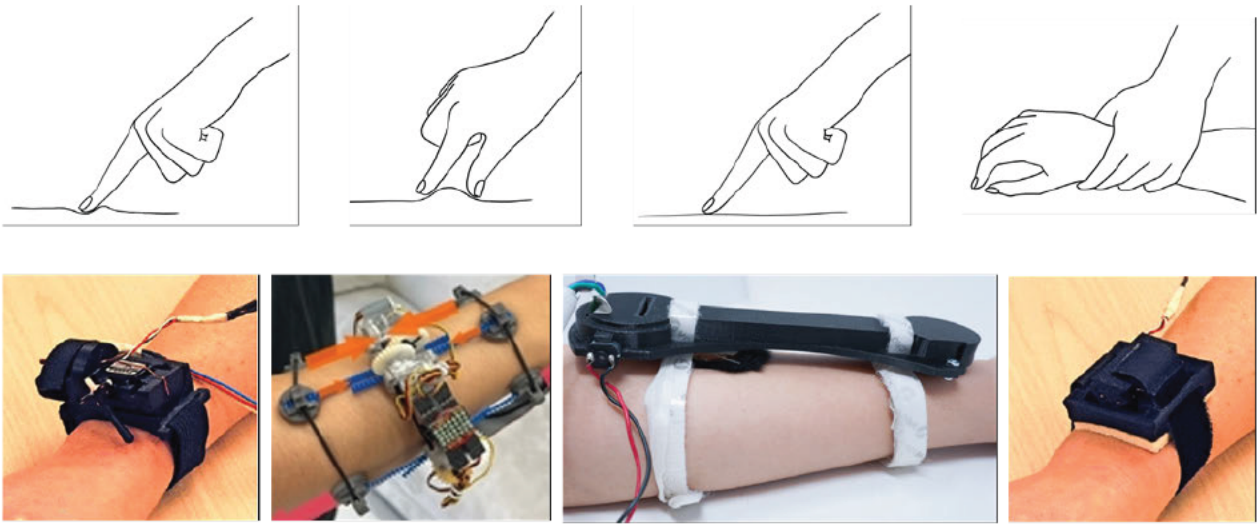


Figure 9 - SMA actuated garment

Electromechanical actuation

With electromechanical actuation, components that convert electrical energy into mechanical motion are referred to. This included servo motors, DC motors and linear actuators. Many mechanical systems and components can provide various types of haptic feedback. Since this research aims to draw a comparison between shape memory alloy and electromechanical actuation, the skin-stretch and compression-type feedbacks are considered.

Skin stretch and compression-type feedback create deformation in the user's skin to provide haptic sensations, by using force, pressure, and friction (Huang et al., 2022). This is done by using shear force, normal force, or a combination of the two (Adilkhanov et al., 2022; Martín-Rodríguez et al., 2024; Pacchierotti et al., 2017). Each type of force produces distinct tactile sensations on the skin, depending on how they interact. For example, when there is increased resistance between a device and the skin, shear force can create a sensation of dragging across the skin. When shear and normal forces are combined, it is possible to produce a feeling such as pinching. If shear force is applied and slipping happens, it could create a sensation similar to stroking. When only using normal force, it could resemble pressing into the skin, or if placed around the wrist, a squeezing effect can be created. In Figure 10 these sensations are visualized, below each sensation, a haptic wearable using electromechanical actuation is shown recreating that sensation.



Dragging
(Stanley & Kuchenbecker, 2011)

Pinching
(Kim et al., 2024)

Stroking
(Zhao et al., 2022)

Squeezing
(Stanley & Kuchenbecker, 2011)

Figure 10 - Skin stretch and compression sensations

Electromechanical wearables

There are already many electromechanically actuated wearables providing skin stretch or compression-type feedback being designed and evaluated. To enable the comparison process, a generalized overview of these devices is created. There are many design choices that can be made, so most haptic wearables differ greatly. This generalized overview will be a useful guideline, however, it will most likely not be able to capture all options fully.

System taxonomy

For the purpose of the project, an overview of all the relevant aspects when designing a haptic wearable, a system taxonomy was made. The image below shows which design decisions are relevant (Figure 11). The system taxonomy regards the provision of haptic feedback, therefore, components such as sensors are not included here. This taxonomy is based on literature in which the design of electromechanically actuated devices is discussed (see Appendix B for references). The relevant design choices discussed in this literature, as well as the components found in their final designs, have contributed to this taxonomy.

From this overview, it becomes clear that there are many options regarding the actuator available as well as the movement translation in the device. This allows for various potential movements of the device, enabling the creation of the exact desired motion. However, for the sensation resulting from this motion, the shape and material of the end-effector are also highly relevant.

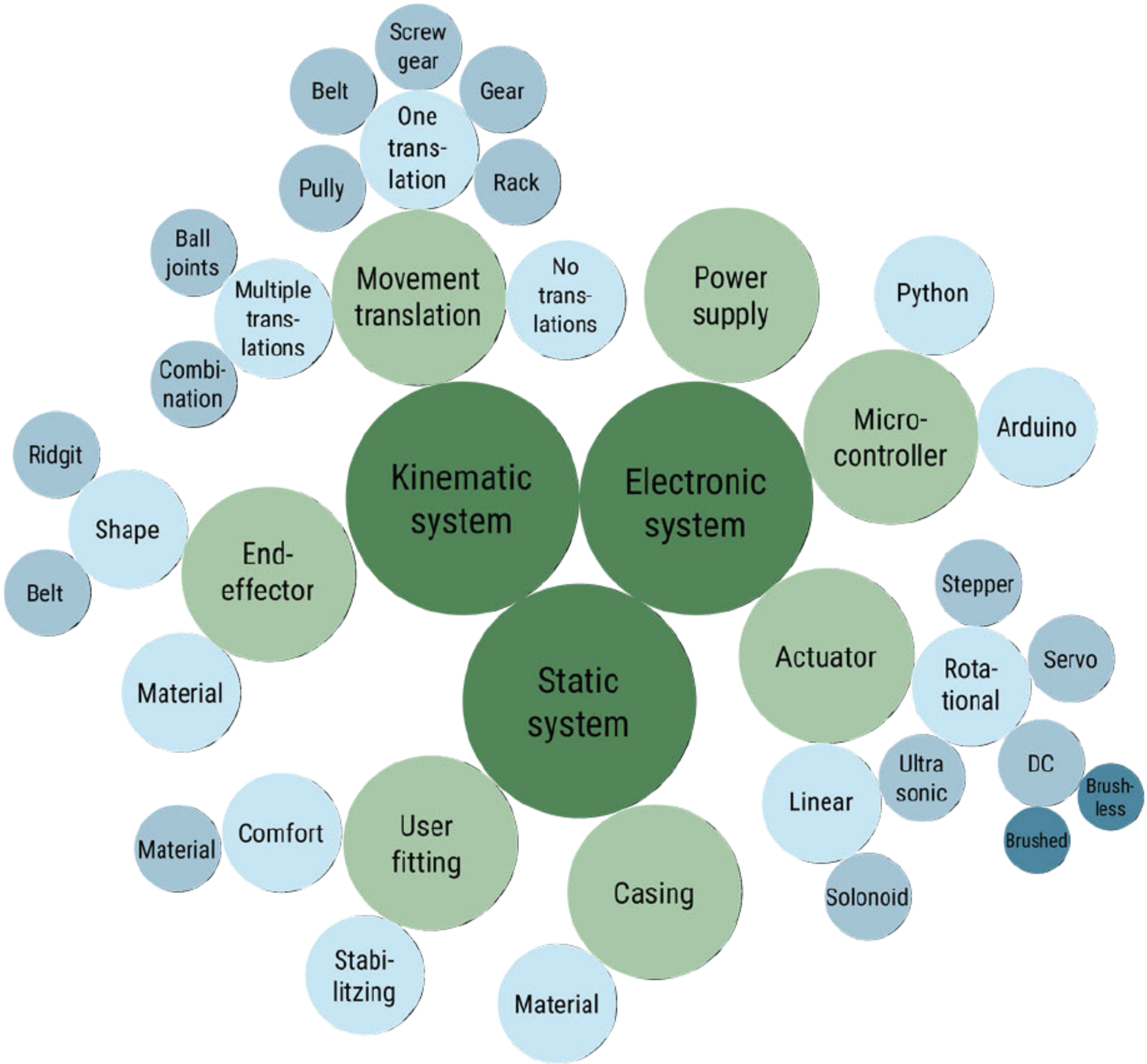


Figure 11 - System taxonomy of electromechanically actuated devices

Evaluation metrics of a electomechancial device

To determine the metrics that are relevant when evaluating haptic wearables, a systematic review was done (see Appendix B). Each paper regarding a haptic wearable providing skin stretch feedback was analysed (citations are given in Appendix B), and technical, performance, and user experience metrics were extracted. Several parameters were mentioned repeatedly when evaluating the devices. This occurrence was tracked, and the most relevant metrics are outlined in the table below (Table 1). In various papers, the terminology does not align completely, therefore, the column 'also referred to as' includes different terms referring to the same concept. To clarify exactly what is referred to with the terms, a short explanation is included.

Table 1 - Evaluation metrics for electromechanically actuated wearables

Evaluation category	Evaluation metric	Explanation	Also referred to as
Technical metric	Displacement	The size of the movement the end effector can make	Actuation area, reach, workspace
	Size	The dimensions of the device	Volume
	Power consumption	The power that the actuator needs to actuate	Voltage
	Weight	The mass of the entire device	
	Force	Refers to the force that can be delivered by the actuator	Torque
	Number of actuators	How many separate actuators are used	
	Degrees of Freedom	In how many planes and axes the device can move	
	Contact area	The area of the device that touches the user	
Performance metric	Reaction speed	The speed at which the haptic feedback cue is given	Completion time, bandwidth
	Expressiveness	How big the ranges of possible cues is	Range
	Controllability	How specifical the output can be controlled. This can regard the angle, speed or extension	Precision, precision of the movement, range of speeds
	Force-to-weight ratio	The amount of force that can be delivered divided by the total weight	
	Accuracy of the interpretation	How accurately the user reacts to the given signal.	Effectiveness, comprehension, recognition
User experience metrics	Ergonomic	How well the device is shaped to the user	Fit, Form factor, Adaptability
	Comfort	Combination of the force applied to the user, weight of the device, and ergonomics	Wearability
	Impairment	The physical influence of the device on the user when wearing	
	Magnitude of the sensation	The experience of the haptic cue from the device	

Shape memory alloy actuation

Shape Memory Alloy is a novel material that can "remember" a predetermined shape (Liu et al., 2023). A certain shape can be programmed into the material, making this material very suitable to use as an actuation method. Unlike electromechanical actuators that rely on external moving parts, such as motors or gears, the motion in SMAs originates from within the material itself. Figure 12 shows where SMA is placed in the world of materials. This shows that the shape can be selected and programmed, and even the timing of returning to the trained shape can be determined.

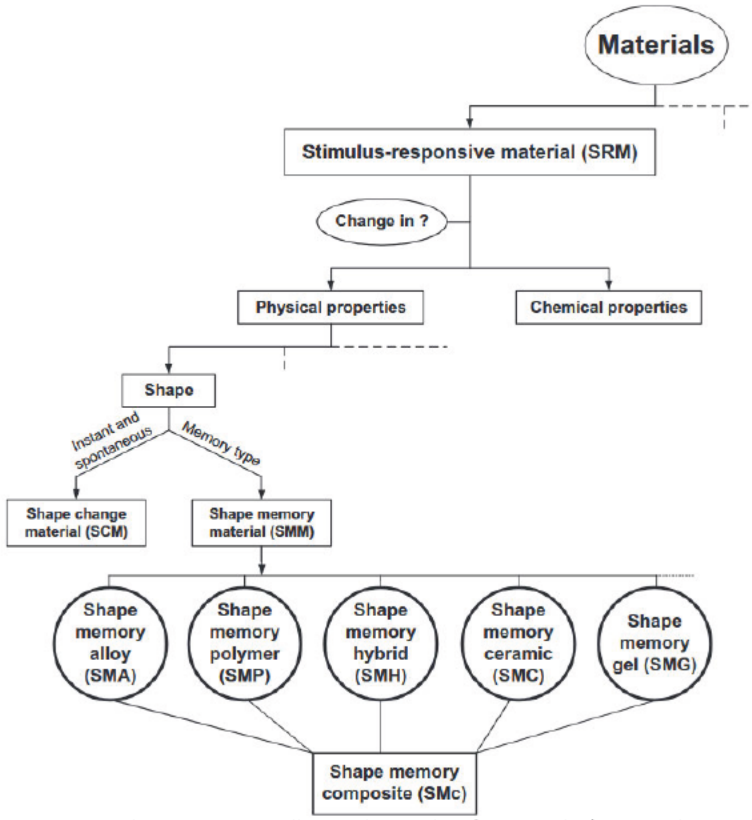


Figure 12 - Shape Memory Alloy in the world of materials (Sun et al., 2012)

Shape memory alloy is a new material that is still in need of research. Back in 1971, the Naval Ordnance Laboratories uncovered significant recoverable strain in Nickel-Titanium alloy, which is why this alloy is nowadays named NiTinol (Sun et al., 2012). There are several other versions of shape memory alloys available, however, NiTinol is currently the most used and reliable wire (Huang, 2002). SMA is already being applied in areas such as automotive, aerospace, robotics and biomedical, as well as in other areas (Mohd Jani et al., 2014). Yet, there are many more opportunities for which SMA can be suitable, such as its usage as actuators in haptic wearables (Yang et al., 2021). In this chapter, the working principle, system taxonomy, and evaluation metrics will be discussed.

Working principle

SMAs are alloys that can return to the shape given to them during training. This transformation phenomenon between two phases is called the Shape Memory Effect (Mohd Jani et al., 2014). When exposed to temperature changes, the internal structure of the alloy transforms at a molecular level, generating movement as a direct response. The SMA can exist in two different phases with three different crystal structures. The crystal structures are the austenite state, the twinned martensite state, and the detwinned martensite state (Figure 13). The material can be applied in three distinct ways: One-way shape memory effect, Two-way shape memory effect, and super-elasticity effect (Huang, 2002).

One-way shape memory effect

When using the one-way memory effect, the material is trained to have one initial shape (Liu et al., 2023). When heating the material to 500 degrees Celsius, the molecules and atoms rearrange in the austenite state, which is how the programmed shape is embedded. When the material cools down, it moves to the twinned martensite state, which means that the material can be deformed freely again. By deforming, or loading, the material changes to the detwinned martensite state. When the material is heated again, the material returns to the austenite state, also changing its shape. This cycle can be repeated many times. This cycle is visualized in Figure 13 with the blue arrows.

Two-way shape memory effect

For using the two-way shape memory effect, the material needs to be trained to remember both a high-temperature and a low-temperature shape. Meaning that both the austenite and the detwinned martensite state have a trained shape the material can change into. This cycle is visualized in Figure 13 with the red arrows. However, this effect has low reversible strain and lack of reliability and is therefore not often used (Nair & Nachimuthu, 2022).

An alternative to the two-way shape memory effect is a biased one-way shape memory effect. In that case, the movement is done in one direction by the material itself, and in the other direction by a bias force, such as a spring. This makes a two-way system using SMAs more reliable than using the two-way shape memory effect (Mohd Jani et al., 2014).

Super-elasticity effect

The super-elasticity (or pseudoelasticity) effect appears in SMAs whose activation temperature is below 0 °C (Liu et al., 2023). When these are loaded at room temperature, they can change in shape by loading, but immediately return to their original shape when this load is removed. This material moves between the austenite and detwinned martensite states without heating or cooling. This cycle is visualized in Figure 13 with the green arrows. Different from the shape memory effect, which can be used to generate motion and/or force, super-elasticity can be used to store deformation energy (Ghodrat, 2020).

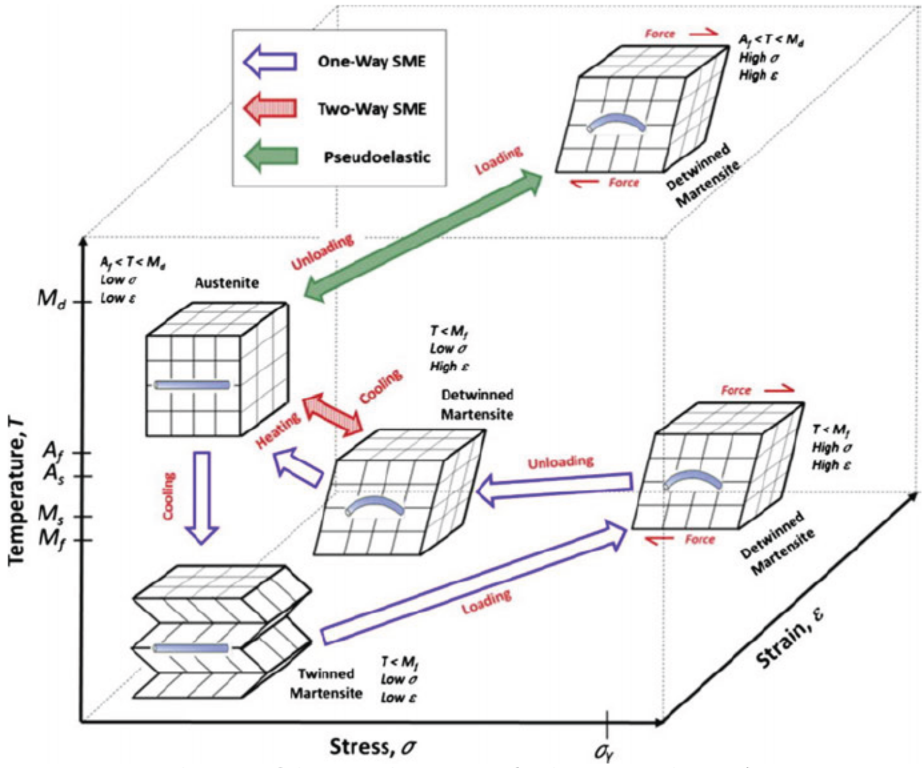


Figure 13 - Visualization of the crystal structures (Mohd Jani et al., 2014)

System taxonomy

Similarly to the previous chapter regarding electromechanical devices, a system taxonomy is made for haptic wearables using shape memory alloy as an actuator (see Figure 14). The build-up of the taxonomy is the same, so the differences are found at more detailed levels.

A big deviation from the electromechanical system taxonomy is found when looking at the detailed level of the movement translation. When using SMA, there is usually no extra movement translation done from the movement created by the material. The second branch that deviates greatly is the one regarding the actuator. When using shape memory alloy as an actuator, there are still many options available on how the desired movement is created. In the following subsection, these options are discussed.

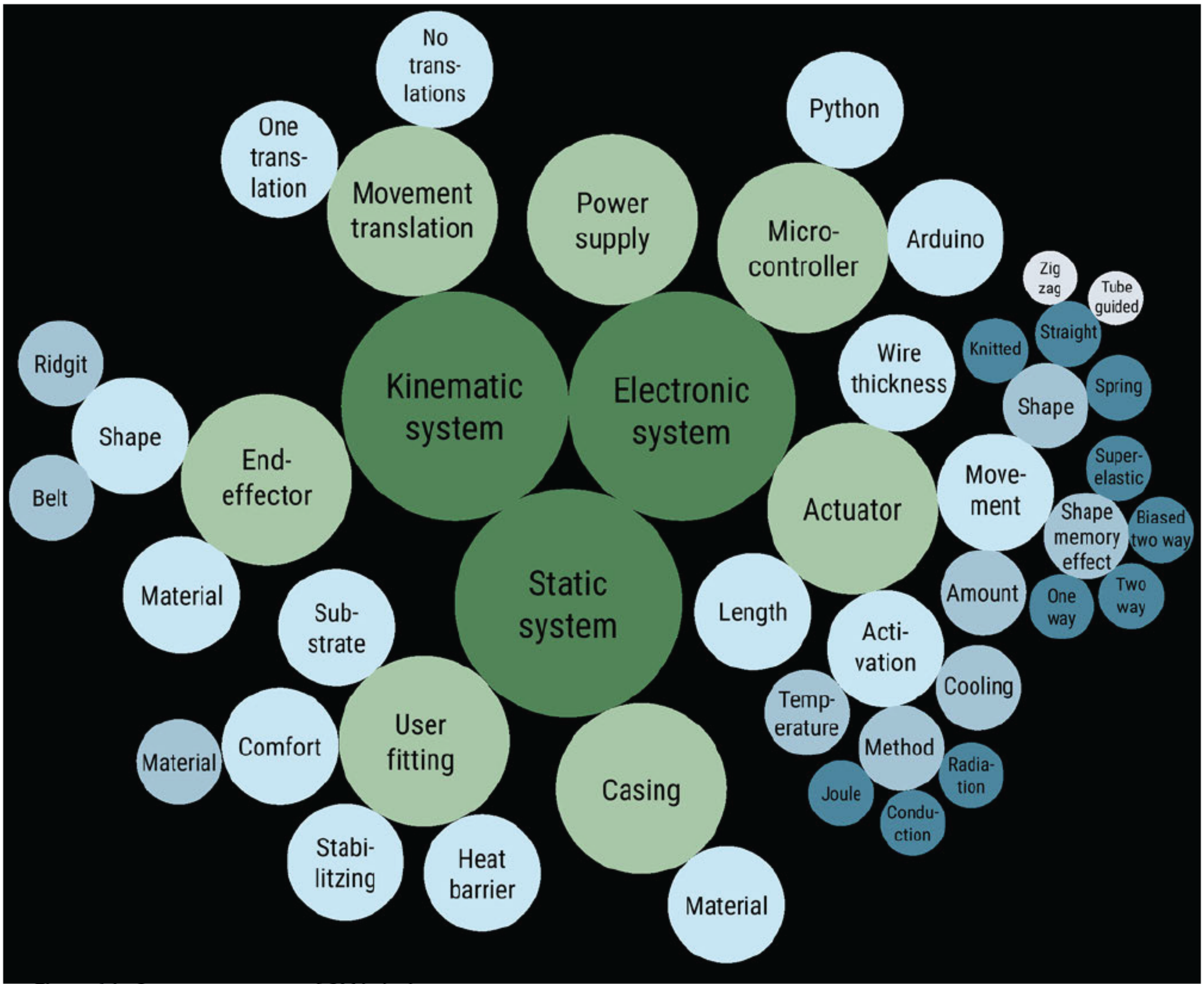


Figure 14 - System taxonomy of SMA devices

SMA wire aspects

There are three main aspects that need to be considered when working with SMA. These aspects are the activation temperature, the wire thickness, and the shape (Liu et al., 2023). Each of these aspects is discussed below, highlighting its impact on the overall system.

Activation temperature

The activation temperature of a Nitinol wire depends on the ratio of Nickel and Titanium in the wire (Reynaerts & Brussel, 1998). This activation temperature is given in a range, which means that the material starts changing when it reaches the lower end of the range, and should be returned to the programmed shape when the upper end of the range is reached.

Heating the wire can be done in different ways (Huang, 2002). First, through thermal conduction, heating a close-laying material such as a resistance wire. Secondly, through thermal radiation, heating the surrounding air or water. Finally, through joule heating, passing electricity through the wire which will then heat because of its electrical resistivity. The most commonly used method in haptic wearables is Joule heating (Liu et al., 2023). By using the following equation (Equation 1), the time needed for the wire to reach the activation temperature can be calculated. By changing the current used, the heating time can also be shorter or longer.

$$t_{heat} = \frac{\pi * d^2 * \rho * C_p * \Delta T}{4 * I^2 * \rho_R}$$

Equation 1 – Heating time formula (Liu et al., 2023)

When working with a specific wire that has a higher activation temperature range, the wire needs more time to reach that temperature and therefore also moves more slowly. Moreover, when, for example, immersing the material in boiling water, the wire with the lower activation range will revert to its programmed shape more rapidly than one with a higher range.

Wire thickness

The wire thickness will mainly influence the heating and cooling time of the material (Liu et al., 2023). This is because a thicker wire has a greater volume, which takes longer to heat up. As the volume increases, the surface-to-volume ratio of thicker wires decreases. This reduction means they cannot lose their heat as rapidly, resulting in a longer cooling time. Therefore, while thicker diameter wires can exert more force, they will have longer cycle times. Another solution could be using multiple strands of thinner wire to achieve a higher force.

Wire shape

The wire can be trained in many different unique shapes. The most commonly used ones are straight, zig-zag, tube-guided, and spring. The shape influences the displacement achieved with the wire, however, the durability is also influenced (Mohd Jani et al., 2014).

When working with the straight wire, the actuation displacement is limited by the actuation strain. For SMA wire this is around 4-8% of the length of the wire (Liu et al., 2023). This is only a small percentage, thus limiting the displacement. Several strategies exist to enhance this process. First, the zig-zag actuator employs pivot points, allowing the wire to zig-zag, increasing its length while maintaining a compact device size (see Figure 15a). Second, the tube-guided actuator channels the SMA through a tube that spirals (see Figure 15b), resulting again in a longer wire while keeping it compact.

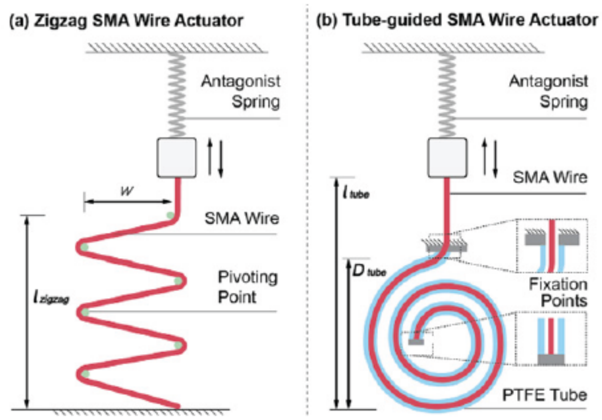


Figure 15 - Methods for extending SMA wire length (Liu et al., 2023)

By programming the SMA into a spring, the displacement is greatly increased. Whilst the displacement increases, there is also a lot more material required to coil the spring. When looking at the wire in tension (occurs when using straight wire), the load efficiency is much higher than in bending (occurs when using a spring) (Mohd Jani et al., 2014). Moreover, the recovery force and strain will reduce by approximately 30% after only 1000 cycles. In Figure 16, two springs are shown that initially had coils with the same tightness. The left spring shows that only after a couple of uses, the coils do not fully return to their trained shape. So while using a spring to achieve significant displacement seems ideal, there are certain drawbacks attached.

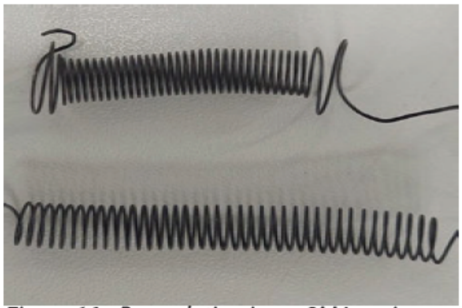


Figure 16 - Degradation in an SMA spring

Evaluation metrics of an SMA actuated device

When evaluating haptic wearables using SMA as actuation, several metrics are often mentioned. Some are similar to the electromechancial actuators, and others are specifically relevant to SMA actuation. Since SMA is a novel material, a lot of research has been done into the wire itself independently, without immediately incorporating it into a device. First, the advantages and challenges mentioned in these research papers are discussed. After this, the evaluation metrics are compiled based on these advantages and challenges, together with the metrics found in papers using SMA in haptic wearables.

Advantages

There are several advantages of using SMA as an actuator that can be useful when designing using the material. The material is simple to use and also very adaptable, meaning that the SMAs are capable of actuating in a fully three-dimensional manner (Ghodrat, 2020), making it easy to work with. Moreover, this facilitates easy combining of multiple haptic feedback cues. The power-to-weight ratio of SMA wires is high, meaning that it is easier to design a lightweight device, making the material suitable for wearable devices (Liu et al., 2023). Furthermore, the material is noiseless when being actuated, which could be a huge advantage for the user experience of a design. Finally, the material works spark-free and is corrosion-resistant.

Challenges

The biggest disadvantage of the SMA wire is the slow reaction speed. The wire can be heated quickly, but this will always have a slight delay (Ghodrat, 2020). However, the cooling time is a bigger challenge to overcome if you want to reach a high cycle speed. This is because the wire needs to cool down before its shape can be changed by using force, slowing down the cycle. The actuation time of SMA actuators can take from half a second up to 30 seconds for one cycle (Liu et al., 2023). There are multiple ways to mitigate this problem, such as active cooling by using air or liquid, however, these solutions also have drawbacks, such as higher energy consumption and noise production (Mohd Jani et al., 2014).

Furthermore, the energy efficiency of SMAs is low. This is because the wires rely on a thermal effect to generate actuation. This means that all energy turns into heat, which results in the movement of the wire. Additionally, the material needs constant energy input to stay in the actuated state (Liu et al., 2023). The maximum energy efficiency of SMAs is around 10-15% (Mohd Jani et al., 2014).

Finally, degradation and fatigue have to be taken into account when using SMAs. When going through many cycles, the SMA material can suffer from functional fatigue. This is due to microstructural changes that result in changes in the activation temperature and loss of memory (Ghodrat, 2020). Depending on the wire and trained shape, the material is stable for 2500-12000 cycles (Nair & Nachimuthu, 2022).

Compiled evaluation metrics

To determine which evaluation metrics are important when designing a haptic wearable using shape memory alloy as the actuation method, a systematic review was done as mentioned in the previous chapter (Appendix B). Additionally, the above-mentioned advantages and challenges were taken into account. In the table below (Table 2), the most relevant metrics are outlined, and the ones determined from the advantages and challenges are marked with an asterisk (*). Again, a brief explanation is included as well as various terms referring to the same concept.

Table 2 - Evaluation metrics for SMA-actuated wearables

Evaluation category	Evaluation metric	Explanation	Also referred to as
Technical metrics	Power	How much power is needed to activate the SMA	Current
	Size	The overall volume of the device	Volume, compact
	Contact area	The area of the device in contact with the user	
	Weight*	The weight of the entire device	
	Force	Force created by the SMA	Contraction force, perceived force, force-to-weight
	Wire diameter	The previously discussed wire thickness	Thickness
	Coil size	The radius of the coils of a SMA spring	
	Number of actuators	The amount of separate SMA wires are used	
	Displacement	The distance moved when the SMA is actuated	Length, deformation, distance
	Degrees of Freedom*	The direction the material can move in	
	Controllability	How specifical the output can be controlled. This can regard the angle, speed or extension	Precision, precision of the movement, range of speeds
Performance metrics	Reaction speed	How quickly the desired movement is completed	Reaction time
	Bandwidth*	The time needed for the SMA to activate and return to their original shape	
	Cycles till degradation*	The material will diminish over cycles	Fatigue, durability
	Power-to-weight*	The force created compared to the weight of the device	Work-to-volume
	Energy-efficiency*	Energy the device takes, compared to the effective output	Energy density, energy-to-volume
User experience metrics	Adaptable*	The material can be shaped in every way	Flexible, modular, ergonomic
	Comfort	The user feels comfortable wearing the device	
	Motion impact	The effect of the device on the movement of the user	Obtrusiveness, portable
	Noise*	The sound the actuation emits	Quiet, silent, noiseless
	Sensation	How the user experiences the applied haptic feedback	Pleasantness, natural feeling

Baseline comparison

The project aims to draw a comparison between shape memory alloy and classic electromechanical actuation. In the following section, the baseline comparison is determined based on knowledge gathered from the previous chapters regarding the actuation methods.
The biggest advantage of SMA over classic mechanics is the fact that the material is very versatile. It is flexible and can be applied in many different ways, whereas classic mechanical actuators are rigid. When using any classic actuator, the shape and size are fixed. However, there are many classic mechanical actuators available with various dimensions and different specifications, offering flexibility to a certain extent.

Whilst the exact specifications of a mechanical actuator cannot be chosen, they are highly controllable. By using the correct coding, the actuators will perform the desired movement precisely with high resolution. In contrast, the extent of the controllability of SMA is limited to activating it either slower or faster. Moreover, there is a maximum speed at which the SMA can be activated. SMA has a slight delay when activated, and especially has a long cooling time, so high cycle speed is hard to achieve. It is, however, easy to combine multiple separate SMA wires to enable a certain level of control by integrating them smartly.

The specification of classical mechanical actuators also largely determines the power-to-weight ratio of a device. As the SMA wire is very lightweight, the power-to-weight ratio is also very likely to be high. Whilst for mechanical actuators, often more power also means more weight (Chen et al., 2021).

Fatigue is a big challenge presented when working with SMA. Significant degradation appears after as few as 2500 cycles. Classical mechanical actuators do not experience fatigue in a similar way. It is more likely that the kinematic system suffers before the performance of the actuator declines. Yet since there is often a more complex kinematic system involved when using classic mechanical actuation, this is certainly something to be taken into account.

Finally, are there several user experience aspects in which SMA is expected to perform better. For example, the noise produced by classic mechanical actuators will hurt the user experience. Additionally, the flexibility of the SMA wire is useful when designing with ergonomics in mind.

Project evaluation metrics

To draw a comparison between different wearables using classic electromechanical actuation and SMAs as actuators, evaluation metrics relevant for both were determined. In the two chapters discussing the actuation methods, the metrics for these actuation methods were discussed separately. In this chapter, these are combined and the final metrics for the project are determined. Before the previously mentioned metrics were included, a general overview was created. Using several papers on the general assessment of haptic interfaces, baseline evaluation metrics were determined (Emami et al., 2024; Hayward & Astley, 1996; O'Malley & Gupta, 2008; Pacchierotti et al., 2017; Wang & Chortos, 2024). Similarly to before, a definition and the "also referred to as column" are included. These metrics are shown in the table below (Table 3).

Table 3 - Evaluation metrics of haptic interfaces in general

Evaluation categories	Evaluation metric	Explanation	Also referred to as
Technical metrics	Degrees of Freedom	The degrees of freedom the device has	
	Size	Refers to the volume of the device	Volume
	Number of actuators	Number of actuators used in the entire device	
	Weight	The mass of the device	Inertia or perceived mass
	Force	The force the device can apply to the user	Torque, max torque/force and force magnitude
	Motion range	The area the end-effector can move in	Displacement, deformation and workspace
	Power	The power needed to actuate	
Performance metrics	Precision	How precise the actuator can be controlled	Resolution, sensitivity range and accuracy
	Power density	The power needed compared to the volume	Power-to-weight
	Actuator speed	How quickly the device moves and reacts	Bandwidth, reaction speed, acceleration and response time
	Degradation	How long the device will work well	Cycle life, durability, reliability
User experience metrics	Comfort	To minimize discomfort and adapt to the user's shape.	
	Impairment	The impact on the user's motion	
	Form factor	The ability to fit to the size of the user.	Device-body-interface
	Weight perception	The impact of the weight on the user	
	Wearability	Influenced by the size, weight, shape, flexibility of the device	Combination of comfort, impairment, form factor and weight perception.

With base evaluation metrics also determined, these three lists were compared. Using this method, metrics were found that are relevant for haptic wearables using both shape memory alloy and conventional electromechanical actuation. In the table below these metrics are shown (Table 4).

These metrics are all highly relevant to the wearables of this project; the metrics most frequently mentioned were weight, size, force, displacement, and actuation speed. In the following paragraphs, these metrics will be explained in more detail. Additionally, each metric was given a range, allowing separate designs to be assessed on a predetermined scale.

Table 4 - Final evaluation metrics for this project

Technical metrics:	Degrees of freedom, number of actuators, displacement, volume, weight, force and power
Performance metrics:	Controllability, power-to-weight, actuation speed, degradation and accuracy
User experience metrics:	Wearability, impairment, ergonomics and magnitude of the sensation

Technical metrics

The technical metrics as mentioned above are: degrees of freedom, number of actuators, displacement, volume, weight, force, and power. The degrees of freedom and the number of actuators of the device were not placed on an axis as these are discrete numerical variables and thus carry little meaning when placed on a numerical axis. To determine the range on the axis for all other metrics, the literature from the systematic review was used (found in Appendix B).

Displacement

The displacement of a haptic wearable refers to the area in which the end-effector of the device can move. Depending on the degrees of freedom of the device, this can be in 1D (a line), 2D (a plane), or 3D (a box). For this project, the degrees of freedom was limited to 1D, therefore the displacement is measured in mm and the increment are linear.

Size

To be able to usefully place the size on a linear axis in the radar chart it was represented as volume. This way the metric became one-dimensional, thus not needing three axes in the chart, facilitating gathering insightful information in one go. The volume of the device regards the full size of the entire device. The range of the axis is in cm^3, therefore logarithmic scaling was used.

Weight

The weight of a haptic device is also referred to as inertia or perceived mass. These terms take into account that depending on which part of the body the device is placed, different weights are acceptable for the user as different body parts are stronger than others. The simple term for the technical weight metric is used: the weight axis is measured in grams. The perceived weight is taken into account in the user metrics. The increments on the axis are linear.

Force

This technical metric is referred to as force. The axis is measured in Newton and labelled linearly.

1 | 3,5 | 6 | 8,5 | 11 | 13,5 | 16

Power

This technical metric is referred to as power and is measured in Watts, this axis is linear. For the axis labelling the data regarding power from the literature is used as well as from specifications found on the actuation devices referenced in the paper.

2,5 | 6,25 | 10 | 13,75 | 17,5 | 21,25 | 30

Performance metrics

The resulting performance metrics are: controllability, power-to-weight, actuation speed, durability, and accuracy. The accuracy of the interpretation of the user is a highly relevant metric when evaluating a haptic wearable. However, this research looks into the difference between actuation methods, therefore the accuracy was not included.

Power-to-weight

This performance metric is referred to as the power-to-weight as this is highly relevant when using SMA. With this metric, the amount of force that is created is compared to the weight of the device. Most papers do not mention exact numbers regarding the power-to-weight of the haptic wearables. By calculating this number approximately by dividing the force by the weight (N/g), a scale from 0 to 1 appears to be suitable.

0,10 | 0,25 | 0,4 | 0,55 | 0,70 | 0,85 | 1

Actuation speed

The actuation speed metric refers to the speed at which a full actuation cycle is completed. Meaning the time the system needs to complete the desired movement and return to its initial position. The speed is therefore measured in seconds per cycle. For SMA this can take up to a minute, while for conventional mechanical actuation the movements can be completed in milliseconds. Therefore, the axis is logarithmical, so small differences on the faster end of the axis are still represented.

0,1 | 0,25 | 0,65 | 1,75 | 4,5 | 12 | 30

Controllability

The controllability metric refers to the influence the designer has over the resulting sensation of the haptic wearable. This could be in the form of influencing the force, the range of the motion, the speed of the movement, and more. The axis will be a seven-point scale, ranging from 1, no control over the resulting sensation, to 7, complete control over the resulting sensation. The scoring method shown below provides a broad framework, however, the ultimate decision is based on a thorough analysis of the results.

1:	2:	3:	4:	5:	6:	7:
No control over resulting sensation	Some control over one aspect	Good control over one aspect	Some control over two aspect	Good control over two aspect	Some control over three aspect	Full control over resulting sensation

Degradation

For the degradation metric, the retention of the entire haptic system is considered. The measurement was taken after the haptic wearable has completed 100 cycles. After these cycles it is determined how much of the performance of the system is retained, then calculating the degradation by reversing the percentage. The axis measurement is in percentages, starting at 30% degradation since the literature showed that SMA can lose up to 30% performance in 1000 cycles, up to 0% degradation.

User experience metrics

To include the user experience metrics in the radar chart together with the performance metrics and the technical metrics is more complicated. However, by using psychometrics methodologies, this was possible (Sauro & Lewis, 2012).

First, the exact meaning of the user experience metrics was determined. From research resulted comfort, impairment, ergonomics, and magnitude of the sensation as the relevant user experience metrics. However, their meanings were not clearly defined. To avoid vague and overlapping meanings of these terms influencing the user test results, exact definitions were determined (see Table 5). This was done in a similar way to the approach of Knight & Baber (2005). In Figure 17, the metrics and their specified definitions are visualized. Additionally, the terms were assigned different subcategories to triangulate the opinions of the users better (Knight & Baber, 2005).

Table 5 - User experience metrics defined

Wearability	The wearability of a device in a social context, in daily life
Disruption	Distraction by the sensation from your surroundings
Emotion	Concerns about appearance and relaxation
Anxiety	Worry about the device, safety, and reliability
Impairment	Does the device obstruct in any way
Movement	The device physically affects movement
Perceived weight	How does the weight feel on your body
Perceived change	Feeling physically different
Ergonomics	Does the device fit your body
Attachment	Physical feel of the device on the body, attachment
Harm	Physical effect, damage to the body
Magnitude of the sensation	How does the haptic feedback feel
Feeling	What does the sensation feel like
Meaning	Can you interpret the movement

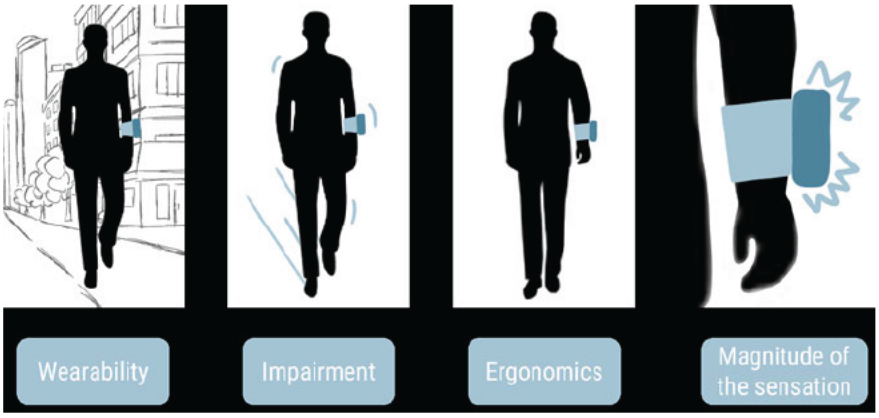


Figure 17 - User experience metrics visualized

Via user tests, the user experience data was gathered by asking the user to answer questions using semantic differential scales (see Figure 18). This gathered data has degrees of intervals (Tullis & Albert, 2013), which means that, while the data is not technically interval data, it can be assumed that the difference between scores 1 and 2 is similar to the difference between 2 and 3. This way the mean of the answers could be compared, and provide insights regarding the experience of the participants.

Figure 18 - Quantifying user experience metrics

Key insights

The literature study was conducted to become familiar with haptics, electromechanical actuation, shape memory alloy actuation, and evaluation metrics. In the following chapter, the key takeaways of the literature study are summarised. With the insights gathered during this study, a project approach was developed.

In the chapter in which haptics was researched, the field of affective haptics and cutaneous wearable devices were selected to continue the project with. Referring to haptic wearables that manipulate the receptors in the top layers of the human skin, aiming to influence the emotions of the user. Additionally, the forearm was identified as a suitable location for haptic wearables, therefore the haptic devices designed during this project were placed here.
Several sensations were determined in the chapter regarding the electromechanically actuated devices as relevant for this project. These sensations were dragging, stroking, pinching and squeezing. Additionally, the system taxonomy of a haptic wearable using electromechanical actuation is determined, identifying the actuator, the moment translations and the end-effector's material and shape as important design aspects of the devices.

The working principle of shape memory alloy was looked into to understand how to incorporate the material into a haptic wearable. The material is activated by heat, and the most suitable method is Joule heating. The system taxonomy that there are many ways in which the wire can be used, with three main aspects: activation temperature, wire thickness, and shape. The biggest advantages identified of SMA are the flexibility, power-to-weight ratio and the noiseless operation.

Finally, the evaluation metrics used for the duration of this project were finalized, based on the relevant metrics for the electromechanical and SMA actuated devices, as well as haptic interfaces in general. Highlighted from these metrics were displacement, weight, size, force, and speed as the most frequently mentioned metrics in the literature. Each of these metrics was defined and assigned a scale to enable the comparison of haptic wearable devices.

By exploring the relevant aspects for comparing the SMA and electromechanical actuation methods in haptic wearables, the outlined takeaways were compiled and used to determine a project approach. In the following chapter, the project approach is presented.

Project approach

The project has determined a focus in the field of affective haptic, using cutaneous haptic wearables on the forearm to provide skin stretch and compression-type feedback. The following main research question was determined:

How do SMA actuators and electromechanical actuation compare in affective haptic wearables?

To answer this research question, a project approach was determined. The analysis consists of two main perspectives: the design process perspective and the user experience perspective. Since the application of affective haptics was selected for this research project, two sensations were selected to look into to create an overview of the vast field of affective haptics.

From the five most frequently mentioned evaluation metrics of haptic wearables, displacement, force, and actuation speed influence the sensation the device creates. Movements such as hitting, pressing, patting, squeezing, and stroking were looked into and assessed on the three metrics (Huisman & Darriba Frederiks, 2013). From this resulted that squeezing and stroking are interesting opposing sensations.

The approach of using two perspectives aims to provide a comprehensive comparison between SMA and electromechanical actuation in haptic wearables, considering both technical performance and user perception. In the following section, the two perspectives are explained, and relevant research questions are formulated for both. The project will involve prototyping, testing, and user studies to address these research questions and generate insights for future designers of haptic wearables.

Design process perspective

A radar chart was used to visualize and compare the performance of SMA to electromechanical actuation across the previously determined evaluation metrics. The radar chart enabled quick comparison between different designs, to enable identification of relationships and trade-offs between metrics. The evaluation metrics ranges are placed on the radar chart with the ideal situation on the outside of chart. A wearable is ideally as small as possible, so the lower end of the range is found at the edge. Conversely, higher force is often desirable, placing the lower end of the force range toward the centre (O’Malley & Gupta, 2008). This way, the radar chart shows clearly which evaluation metrics a device performs well on and which it scores lower on. In the image below, the complete radar chart is shown (see figure 19).

Research questions

From the design process perspective, the aim is to establish guidance for designers regarding working with either SMA or electromechanical actuation. The following research question was formulated to capture this:

How does the choice of actuation method (Shape memory alloy actuation compared to electromechanical actuation) impact the design process of a haptic wearable?

To ensure insightful results answering the above research question, the following sub-questions have been determined. These sub-questions highlight different aspects relevant to the design process.

- What correlations between evaluation metrics emerge when designing with each actuation method?
- What are the advantages and disadvantages of using either SMAs or electromechanical actuation in haptic wearables?
- In which scenarios are either SMAs or electromechanical actuation preferable over the other?

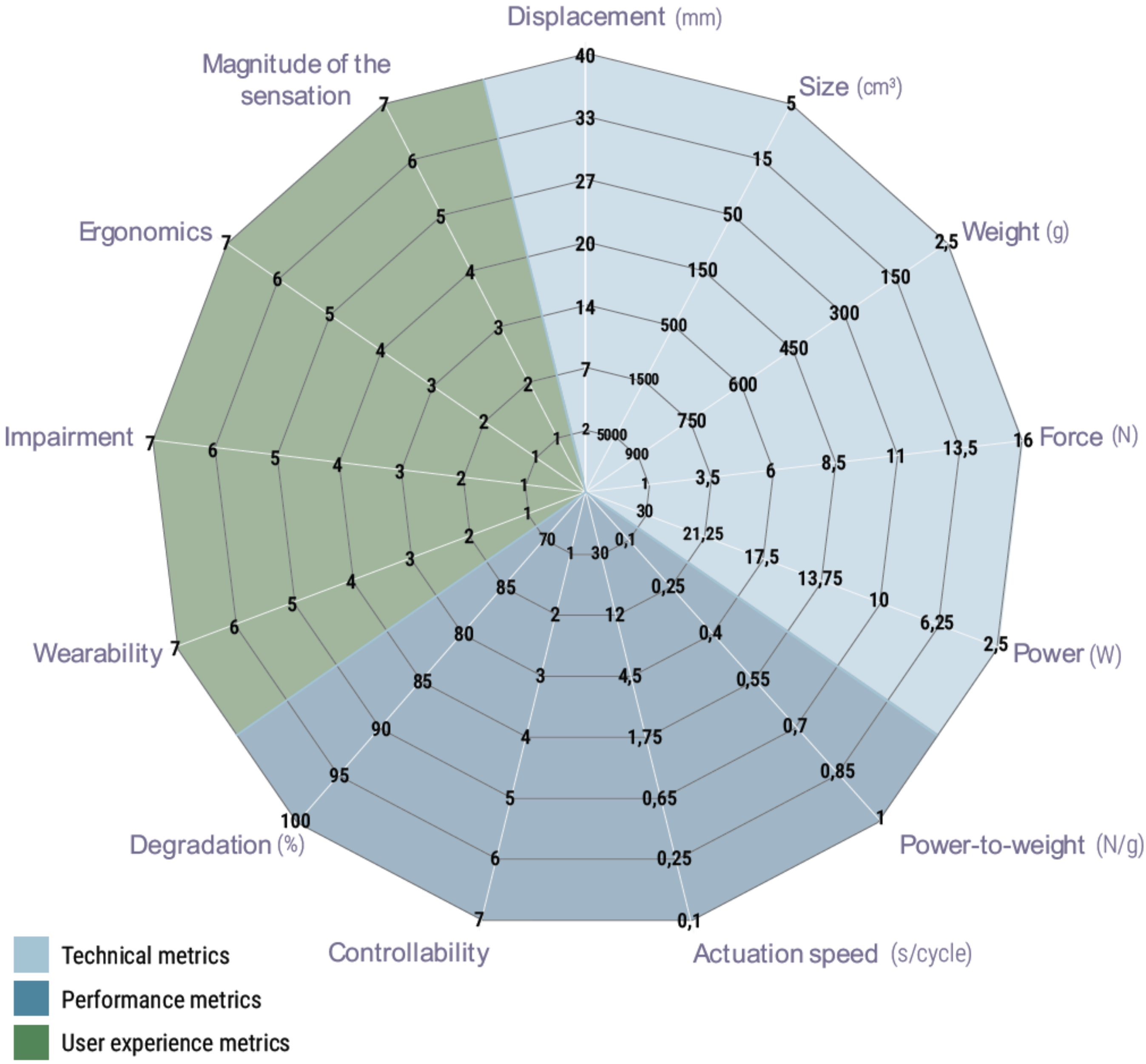


Figure 19 - Radar chart with all evaluation metrics

User experience perspective

Since the project regards the field of affective haptics, the user experience perspective is very important. A squeeze and a stroke can have a different influence on the experience of the user depending on the exact sensation that is created. Therefore, in the user experience perspective, a varying metric is introduced.

Squeezing

A squeezing sensation can be created using a low displacement and quick actuation speed. The force used can influence the emotion that is evoked in the user, therefore, two intensity levels of force were tested. This can create a comforting squeeze or a more alarming squeeze (Huisman & Darriba Frederiks, 2013).

Stroking

A stroking sensation is created by using a bigger displacement and a low amount of force. In this case, the movement speed can affect the emotion felt, so it was examined in two modes (Raisamo et al., 2022). For example, resulting in a loving or excited stroke, or a more unsettling stroke, causing feelings of disgust (Huisman & Darriba Frederiks, 2013).

For each of these sensations, haptic wearables were designed with both shape memory alloy and conventional electromechanical actuation. By conducting user tests, the experience of the user was looked into. Additionally, the influence of varying speed or force on this experience was tested.

Research questions

To identify the effects of the actuation methods on the experience of the sensation of the user, the following research question is compiled:

How do shape memory alloy and electromechanical actuation influence the user experience?

The following sub-questions are defined to highlight different aspects of the user experience. highlight different aspects relevant to the design process.

- How do the different actuation methods and varying force or speed influence the enjoyment of the user?
- How do the different actuation methods and varying force or speed influence the interpretation of the sensation of the user?
- In which scenarios are either SMA or electromechanical actuation preferable over the other?

Design Phase

Following the project approach, four haptic wearable devices were designed. Two squeeze devices and two stroking devices, actuated by either actuation method. In the following chapter, the design process of the four haptic devices is discussed. For the design phase, autobiographical evaluation was used. This method was selected because the design phase was short and quick decisions were needed, especially as four devices needed to be designed. In addition to the autobiographical evaluation, the devices need to adhere to certain requirements, which are explained in the following section.

Requirements

The design process began with the determination of the requirements. Since the sensations were selected based on their performance in actuation speed, displacement and force, requirements were set for these metrics.

The squeeze was selected as a short but intense sensation. For this sensation, low displacement and high actuation speed are determined, and a varying force was tested. Based on Yang & Zhu (2023), Gupta et al. (2017) and Stanley & Kuchenbecker (2011) the requirements for the varying force were determined. For the low-force squeeze 5N was selected, and for the high-force squeeze 15N was selected (Figure 20).

Figure 20 - Requirements of the squeezing sensation

Figure 21 - Requirements of the stroking sensation

A stroking movement was selected as a longer but softer sensation. A big displacement with low force occurs with this sensation, where a varying actuation speed was looked into. From the radar chart, a displacement of 4cm was determined, because this is the biggest displacement found in the analysed literature. Based on Perini et al. (2015) and Löken et al. (2009) the actuation speed was determined. A comfortable actuation speed lays between 1 and 10 cm/s for humans, because of the receptors in the top layers of the skin. An ideal speed is 3cm/s, therefore for this project this speed was selected as the low speed variation, with 10cm/s selected as the high-speed variation (Figure 21) .

Constraints

Since only six weeks of prototyping were available for this project, prototyping limitations have been set. The prototypes were compiled of easily accessible, affordable components. Mainly the production solutions 3D printing was used for the static and kinematic systems, as this is readily accessible to this project. For the electronics an Arduino board was used, together with compatible electronic components. The shape memory alloy wire used were also be selected from types of wires already in possession.

SMA actuated devices

There were several shape memory alloy wires accessible to this project. Wire with 0.5mm thickness and an activation temperature of 50 – 70 Degrees Celsius, wire of 1mm thick with an activation temperature of 45 to 50 degrees Celsius, wire of 1mm thick with an activation temperature of 15 to 20 degrees Celsius, and finally wire with a thickness of 0.5mm with an activation temperature of 15 to 20 degrees Celsius.

For each sensation a separate design process was completed, in the following sections these are described.

Squeeze device

In the following section are the design process and final design of the SMA actuated squeeze device discussed.

Design process

The design process started by drawing several concepts, see Figure 22. From these, three concepts were selected for prototyping: one spring (Figure 22A), two parallel springs (Figure 22B), and a zig-zag (Figure 22C). These designs were all attached to a base layer that was wrapped around the wrist. Therefore, the substrate was very important as the heated wire wrapped around the wrist could hurt the user.

Kino sporting tape and cool tape were tested as these materials are more often used together with SMA. The method for testing these substrates was to create a set-up with a thermocouple at the bottom, on which the different substrates were placed, with finally a SMA wire on top so it could heat up and react to this heat. The sporting tape and cool tape were tested separately and in combination with each other. The test showed that the sporting tape worked better than the cool tape, however the combination worked best for shielding the user from the heat, see figure 23.

The first prototype was created using the combination of the two materials as the substrate. However, when the squeezing sensation of this first prototype was tried, a lot of the sensation was dampened by the cool tape, since this is a more rigid material. Which is why the following prototypes used only sporting tape as a substrate.

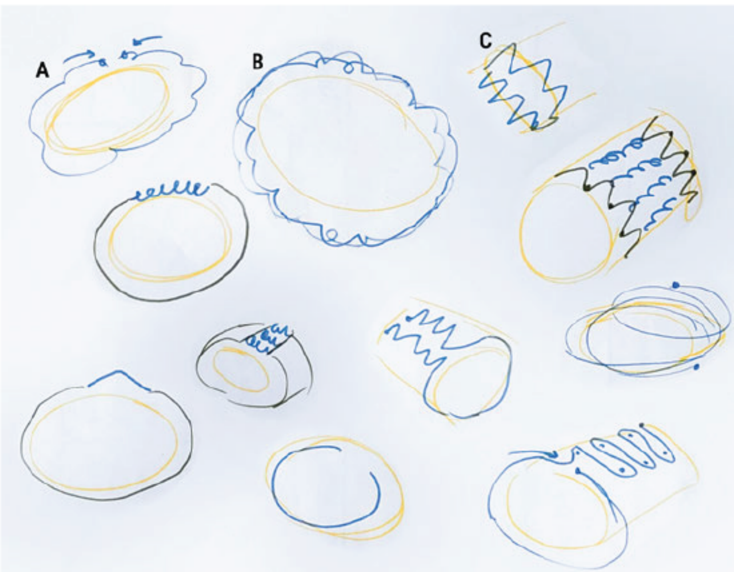


Figure 22 - Concepts for a SMA actuated squeeze device

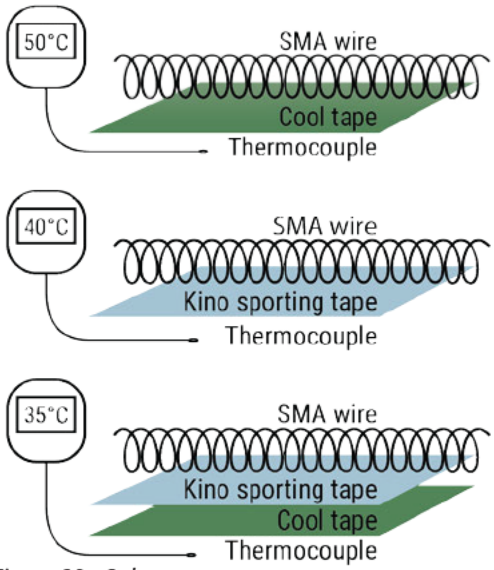


Figure 23 - Substrate tests

The created prototypes worked as intended, so the created force was then tested using a force sensor. In Figure 24, the setup is shown, and the force sensor used is a FSR402. The zigzag SMA wire created a low squeezing effect of 5N. The single spring prototype created a squeezing effect of 10N. Lastly, the double spring prototype created a squeezing effect of 15N, reaching the required 15N determined. The double spring concept was selected as a result of these measurements.

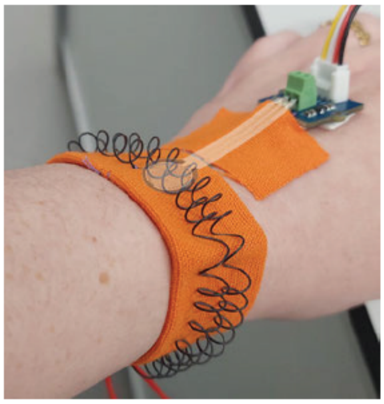


Figure 24 - Force testing setup

After conducting a pilot study, the heat created by the SMA wire appeared to be too hot for comfort. Therefore, another material for the substrate was necessary. As the cool tape was too rigid, a more flexible material was needed. A silicone mat was added to the prototype, after which the temperature underneath the substrate was measured again. The temperature below the silicone mat in combination with the sporting tape did not rise above 30 degrees Celsius. The force of the squeeze effect was also re-measured. The silicone mat did lower the force of the prototype slightly, however, by shortening the springs (reducing the number of coils) this was again increased to 15N.

Final design

The final SMA squeeze device includes two springs. The two springs were made using 0.5mm SMA wire with an activation temperature of 50 to 70 degrees Celsius. The springs consist of 30 coils with a diameter of 6mm, resulting in a total length of approximately 57cm. The substrate is created with sporting tape and a silicone mat. The silicone mat is 2.5cm wide and 15cm long, the sporting tape is wrapped around this layer of silicone. In Figure 25, a schematic of the final design is shown and in Figure 26 the realized design is shown.

This squeeze device creates a low squeezing effect of 5N by running electricity trough the SMA wirer using a power supply, with the settings 3.5V and 2.9A and turning it on for 2.5s. A high squeeze effect is created by setting the power supply to 5V and 3.7A and turning it on for 4s.

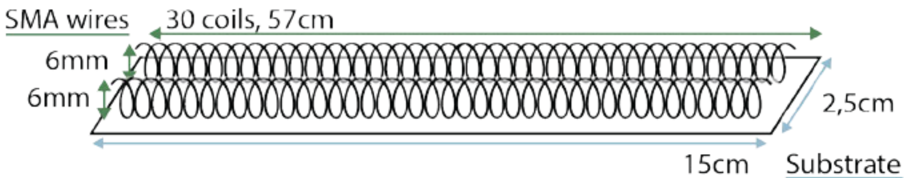


Figure 25 - Schematic design of the SMA wire creating a squeezing movement

Figure 26 - Final design of the SMA actuated squeeze device

Stroking device

In the following section are the design process and final design of the SMA actuated stroking device discussed.

Design process

Several concepts were designed, see Figure 27, for the stroking device using SMA as actuation. The concepts mostly used SMA spring in their design, therefore, a first prototype was created using a SMA spring opposing a normal metal spring (Figure 27A). This quickly demonstrated that the balance between the SMA spring and the bias spring is highly important. From this test, it was also found that a normal metal spring would not work as a bias spring. Therefore, the following tests used SMA wires in which the super elastic effect appears.

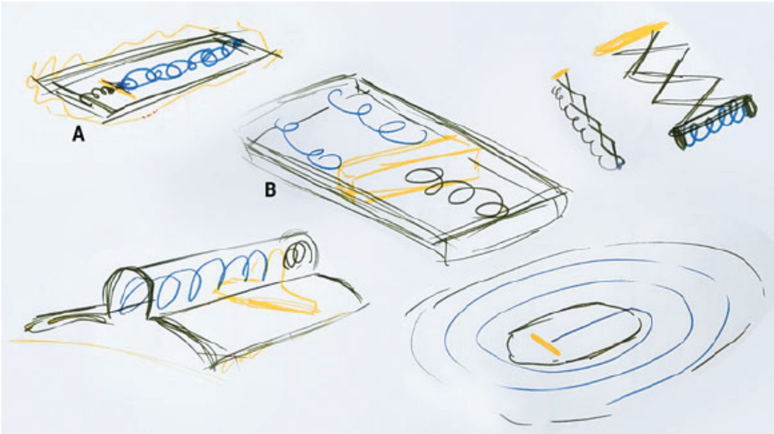


Figure 27 - Concepts for the SMA actuated stroking device

The following prototype consists of a 1mm thick super elastic SMA wire, opposing a 1mm thick SMA wire reactive to heat (See Figure 28A). When testing the set-up, the desired movement of 4cm was achieved, however, the time it took for the wire to cool down and the device returning to its initial position took up to several minutes. To mitigate this, two 0.5mm SMA springs reactive to heat were used opposing the 1mm super elastic SMA wire (the concept in shown Figure 27B and the realised design in Figure 28B), however, this did not appear to be balanced yet. Therefore, a third version of this setup was created using a 0.5mm super elastic SMA wire, opposing a 0.5mm SMA wire reactive to heat (see Figure 28C). For this setup the cooling time was much shorter, within a minute, and better manageable.

By trial and error, the length of the super elastic SMA wire and the SMA wire reactive to heat were determined. The placement of the orange tape shown in Figure 28C enabled quick tests regarding to the created displacement. Aiming for the shortest combination that still reaches the desired 4cm of movement. After determining the full length needed, a casing and an end effector were designed for the device, which were then 3D printed. The initial 3D printed casing and end effector proved to have too much friction for the SMA wires to move the end effector back and forth. Therefore, slots for small metal rods were created in the 3D model, so the end effector would experience less friction, enabling a smoother movement.

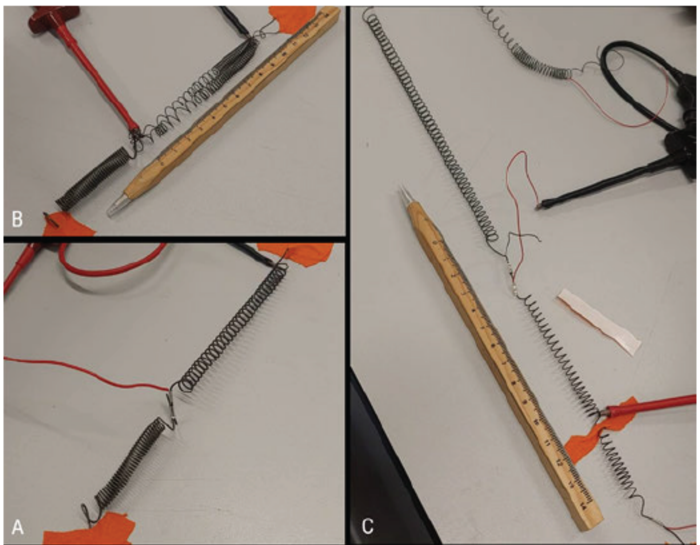


Figure 28 - Trial and error prototypes stroking device SMA

Final design

The final design of the stroking device actuated by SMA wire includes one SMA spring reactive to heat, and one super elastic SMA wire. The super elastic SMA wire is 0.5mm thick and has 20 coils with a diameter of 6mm, resulting in an approximate wire length of 38cm. The SMA wire reactive to heat has a thickness of 0.5mm and has 15 coils with a diameter of 6mm, resulting in an approximate length of 29cm. In Figure 29, a schematic of the final design is shown.
The casing of the final design is 30 cm in length with a channel for the SMA wires with a radius of 8mm. A gap for the end effector was created at 9 cm distance from the edge of the casing for the super elastic SMA and 8 cm for the SMA reactive to heat. The gap itself is 4,5 cm, so the end effector can reach the desired 4cm of displacement. The area of the end effector that would be in contact with the user is covered with leather. In Figure 30 the realised design is shown.

To achieve the differences in speed of the stroking movement, the volt and ampere levels are determined. A slow movement of 3cm/s is achieved with 4V and 3.2A, a higher speed of 10cm/s is achieved with 4.6V and 3.7A. The duration of the movement is determined by the speed.

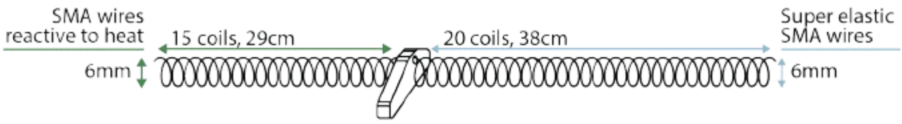


Figure 29 - Schematic design of SMA wire creating a stroking movement

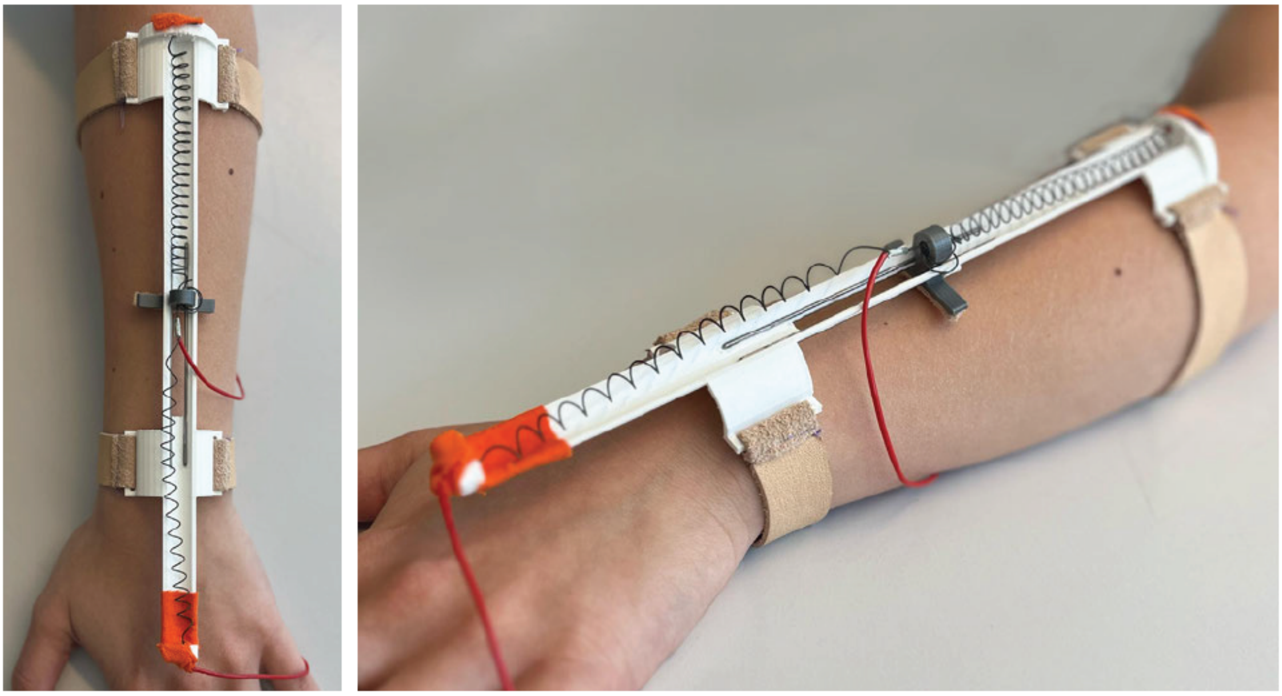


Figure 30 - Final design for the SMA actuated stroking device

Electromechanically actuated devices

To realize the electromechanically actuated devices, Arduino components are used in combination with 3D printed casing and parts. In the following section, the design processes and the final designs for both sensations are discussed.

Squeeze device

In the following section are the design process and final design of the electromechancally actuated squeeze device discussed.

Design process

To start the design process, several concepts were developed (see Figure 31). Most concepts were built around the working principle of shortening a strap around the wrist by rolling it up. The first concept selected for prototyping was one applying this principle with one servo motor (Figure 31A).

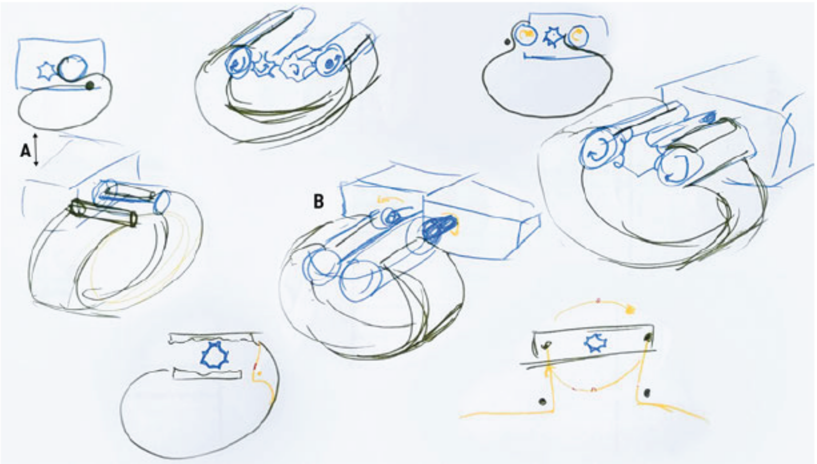


Figure 31 - Final design for the SMA actuated stroking device

A mounting plate for the servo motor was 3D printed, as well as a gear that attached to the servo motor and a strap winder part that rolls-up the strap. To create a squeezing sensation the mounting plate has to be kept stable on top of the wrist. Initially elastic was used to attach the mounting plate to the wrist, and for the strap a wide ribbon was used. When trying the sensation created by this first prototype, it appeared that elastic to attach the device is not suitable. It decreased the squeeze experience from the strap as the elastic already squeezed the wrist tightly to stabilize the mounting plate. Inspiration from watches and bracelets was taken and a leather band was tested for attaching the mounting plate to the wrist. The leather band worked well, the material was comfortable on the skin and the mounting plate was stabilized well. Therefore, the leather material was also tried as the squeezing band for the device. Additionally, Yang & Zhu (2023) have shown that leather receives a high valance score when in contact with the skin. Meaning that participant had positive associations with haptic sensation created with the material, which made the material suitable for this project as well.

The prototype was then tested to discover the peak force created. From these tests it appeared that the prototype using one servo motor stalled at a maximum squeeze effect of 12N. The prototype did demonstrate that the principle of rolling up the strap worked well, therefore, the decision was made to switch to a similar design using two servo motos (Figure 31B).

For the next prototype, the positioning of the servo motors was of importance. When positioning the servo motors similarly to the initial design next to each other, the width of the device exceeded the wrist and stabilizing the mounting plate would become challenging. From several designs, see Figure 32, the design in the bottom right was selected (Figure 32A). The servos in this design are positioned upright with the output shaft at the top to reduce the width of the device as much as possible.

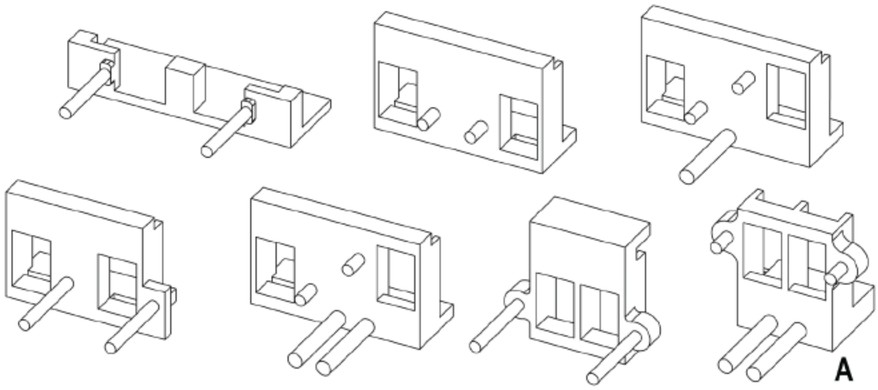


Figure 32 - Concepts for a squeeze device using two servo motors

In this new design the leather strap is pulled into the device, see Figure 33 , which caused the skin of the user also being slightly pulled into the device. This created a painful pinching sensation, which diminished the squeezing sensation that was aimed for. Additionally, there appeared higher forces pulling down on the strap winder parts, which caused them to detach from the device. To mitigate these problems, a closing cap was designed for the device, see Figure 34. This closing cap includes a thin layer that is placed between the device and the wrist of the user at the location where the strap moves into the device and two channels where the endings of the strap winder parts are placed.

When the prototype was finalized, the differences in squeeze force were determined by adjusting the Arduino code. To create a lower squeeze effect of 5N, the strap has to be shortened only a little. Meaning that the number of steps the servo motors have to take is lower.

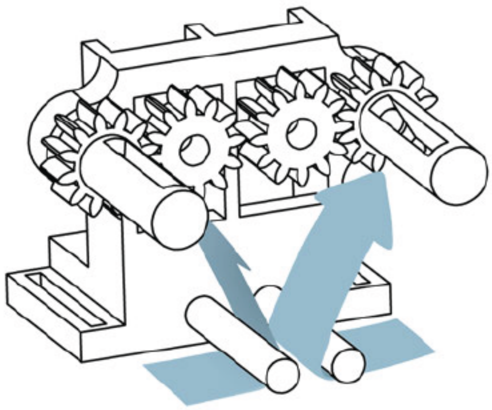


Figure 33 - Pulling direction of the squeeze strap into the device

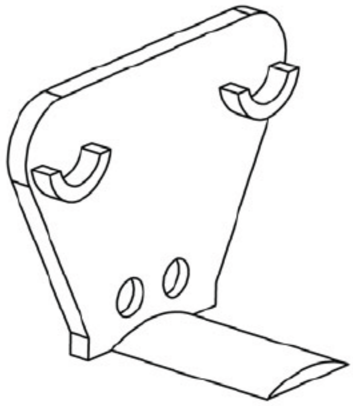


Figure 34 - Closing cap

Final design

The final design for the mechanical squeeze device uses two servos motors as actuation. These servos a fit into a 3D printed mounting plate and to the output shaft of the servo motors a 3D printed gear is attached. The mounting plate is attached to the wrist of the user with leather bands connecting at the underside of the wrist using Velcro. The mounting plate include two protruding rods at the bottom, close to the wrist, that guide the strap from around the wrist to up into the device. The mounting plate also has pegs on which the gears attached to the strap winding parts are placed. A closing cap is attached to the mounting plate at the end of the guide rods, using screws. In figure 35 is shown how the separate components fit together. In figure 36, the final design is shown.

To actuate the servos an Arduino code was used, the full Arduino code is found in Appendix C. The variable named “steps” controls the rotation of both servo motors. To create a squeeze effect of 5N this variable is set to 110 and to create a high squeeze effect of 15N this variable is set to 140.

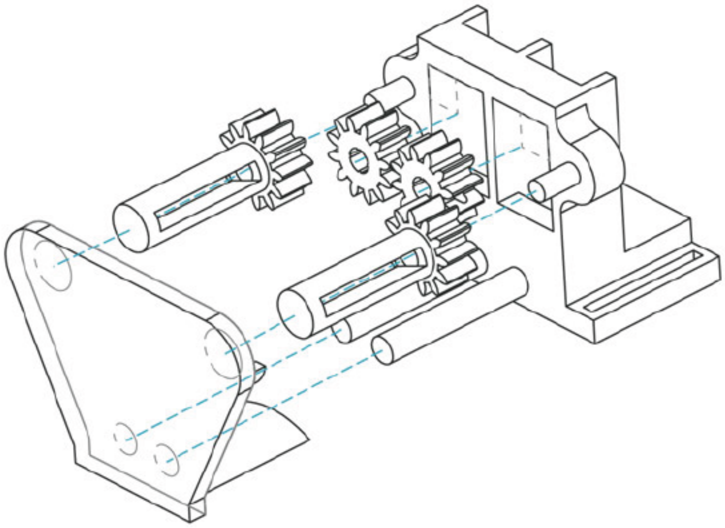


Figure 35 - Exploded view of the mechanically actuated squeeze device

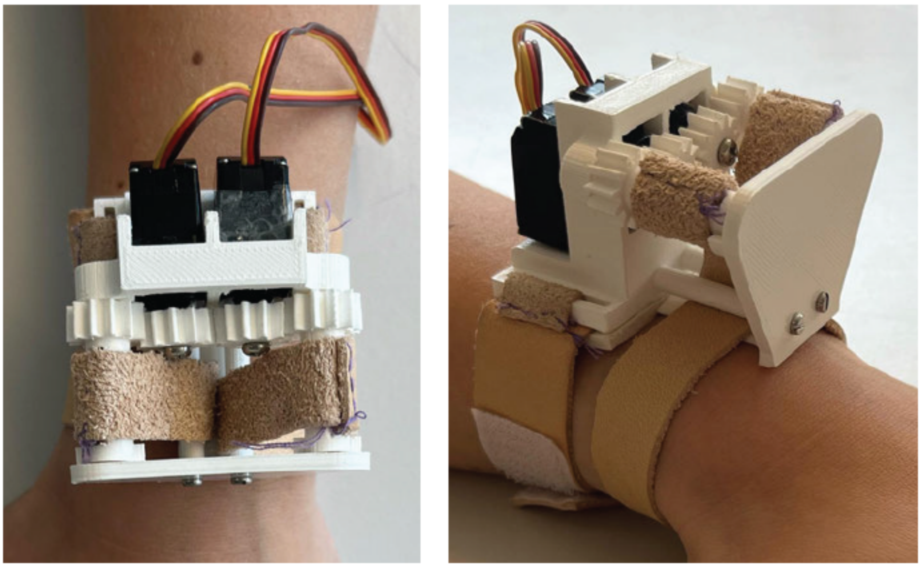


Figure 36 - Final design of the mechanically actuated squeeze device

Stroking device

In the following section are the design process and final design of the electromechancally actuated stroking device discussed.

Design process

To create a stroking sensation using conventional mechanical actuation there are several solutions. In figure 37 the developed concepts are shown. The design using a rack and gear was selected as the most suitable option (Figure 37A).

The initial design was using a servo motor, however since a servo motor only has a rotating reach of 180 degrees, the linear displacement was not enough. A DC motor was tried secondly, but the rotational speed was too high to achieve the determined speed for the stroking sensation. Finally, a stepper motor was tried. This motor could achieve the low-speed setting of 3cm/s, but the higher speed was not achievable outright. For this project, limitations were imposed on components to easily accessible parts, so a fourth type of motor was not tried. Instead, a mechanical design solution was devised to increase the linear speed resulting from rotational speed of the motor.

Gears can influence the linear speed via the rotational movement. By increasing the size of the gear, the linear movement also increases. However, to achieve the determined 10cm/s, the gear would need to be 12cm in diameter, and since a wearable was designed this was not suitable. Therefore, a bigger gear is attached to the stepper motor, which connects to a small gear. The smaller gear has a higher rotational speed, because of this. By attaching a larger gear directly to the small gear, the linear speed at the edge of the large gear is increased. With these movement translations through gears both the high and low-speed requirements can be met. In figure 38 the gears are displayed.

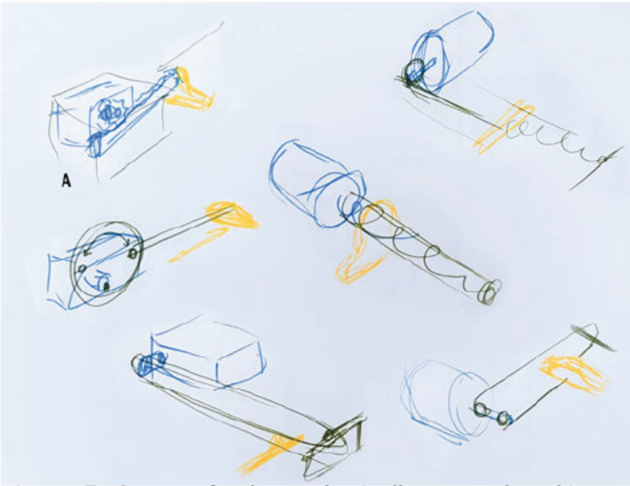


Figure 37 - Concept for the mechanically actuated stroking device

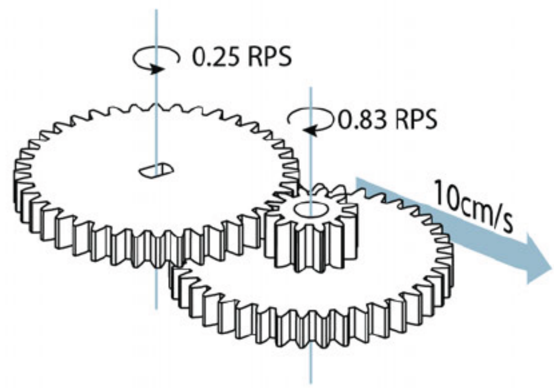


Figure 38 - Gears used in the stroking device

Final design

The final design of the mechanical stroking device uses a stepper motor as actuation. The stepper motor is attached to a mounting plate. Directly to the output shaft of the stepper motor a gear with a diameter of 4 cm is attached. All gears have a modulus of one. A smaller gear connects to this initial motor gear with a diameter of 1.2cm. Layered with this small gear is a gear with 4cm in diameter again. The mounting plate has a peg around which the layered gear is rotating. Additionally, the mounting plate has a channel in which a rack moves back and forth, actuated by the final gear. At the end of the rack, the end effector is placed so it moves over the arm, which is covered with leather. In figure 39 the design of the device is shown, in figure 40 the final device is shown.

To actuate the stepper motor an Arduino code is used, found in Appendix D. The speed is controlled by a delay, named ‘t’ in the code. A higher delay means slower rotation, a speed of 3cm/s is achieved with a delay of 3500. The speed of 10cm/s is achieved with a shorter delay of 1030.

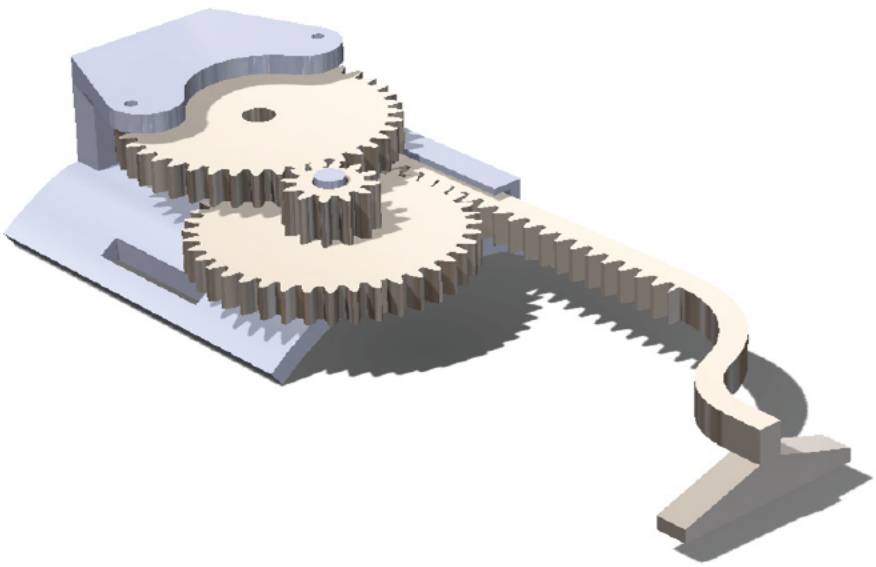


Figure 39 - Design of the mechanically actuated stroking device

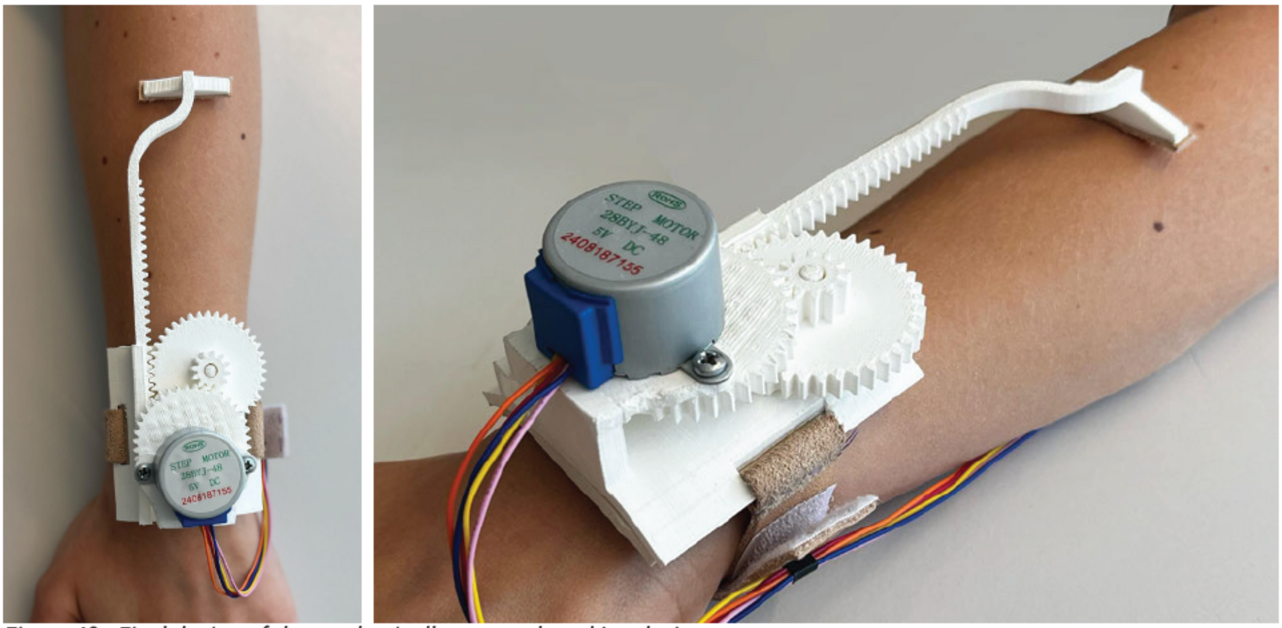


Figure 40 - Final design of the mechanically actuated stroking device

User evaluation

To discover how the user experience is affected by the actuation method, a user test is set up. In the following section, the test set-up and the results are discussed. In Appendix E the complete user test plan is found.

User test set-up

The user test set-up consists of four haptic wearables, a microcontroller, a power supply, and a visual barrier. The participants moved their arms behind the barrier such that their view was blocked. Two different devices were fitted (one on each arm) producing the same sensation on both sides. The mechanically actuated devices were actuated using an Arduino. The SMA actuated devices were activated using a power supply. In Figure 41 the set-up of the user test is shown.

The participants experienced a sensation and then gave their opinions on it. When first experiencing a sensation, open questions were asked. Thereafter, for each sensation they experienced they answered five semantic differential scale questions. The participants provided their answers verbally, which were then recorded by the interviewer.

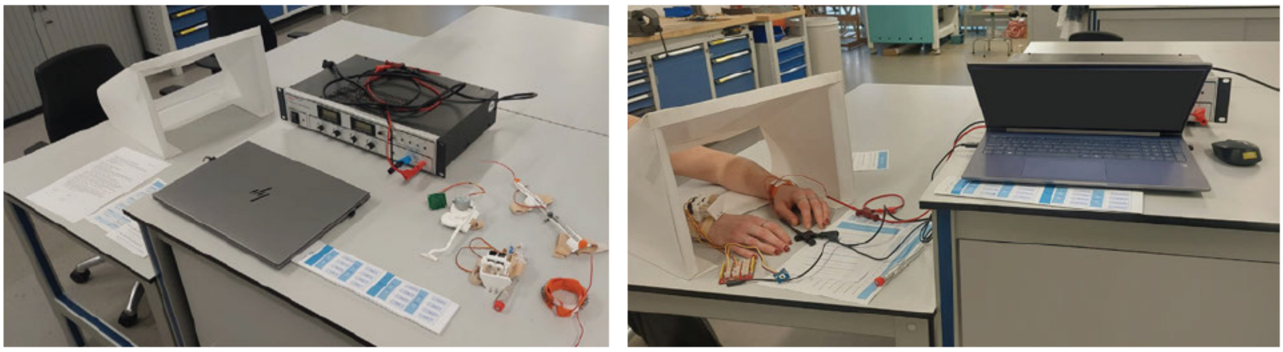


Figure 41 - User test set-up

Method

The user test consisted of two segments, one addressing the squeezing sensation and one addressing the stroking sensation. A segment was opened with an introduction to the sensation, to allow the participants to get familiar with the devices and the sensations. Here the participant experienced the sensation where the force or speed was averaged as not to influence the data of the following section. The force of the squeeze was 10N and the speed of the stroke was 6cm/s. After each of the actuation methods, they gave their first impressions and opinions regarding the sensations. Then they were also asked to compare the sensations and highlight the differences if they felt any. The aim of this introduction to the sensation was to gather unbiased feedback from the participants through open questions. Additionally, the initial surprise and stress the participants might experience was dissipated and would not influence the data gathered in the following section through semantic differential scale questions. Participants got familiar with the experience during the introduction and thus were able to better focus on the differences between the sensations in the following section.

For each segment, there were two subsections. Between these subsections, the devices were switched to the other arm, this way both actuation methods were felt on each arm and the gathered data was not influenced by this. Within the subsections, four sensations were experienced, two for each actuation method with a varying force or speed. The order of the variations was also be randomized. After experiencing a sensation, the participants were asked to answer five questions given as semantic differential scales. These questions were about pleasantness, intensity, humanlikeness, force/speed and the underlying feeling of the sensation.

After the two subsections were completed, the participant was allowed to see the devices. One final subsection regarding the device impressions of the participants was then addressed. The participants were asked several questions about the experience of wearing the devices, again in the form of semantic differential scales. These questions were answered once for each actuation method on either arm.

For the second segment, the same structure described above was followed. The complete structure of the user test is visualized, shown in figure 42, with arrows indicating where the order would be randomized per participants. When the user test was completed, each participant has experienced sixteen sensations, each distinct sensation being repeated twice, with the order of actuation method and varying force or speed applied randomly for each participant.

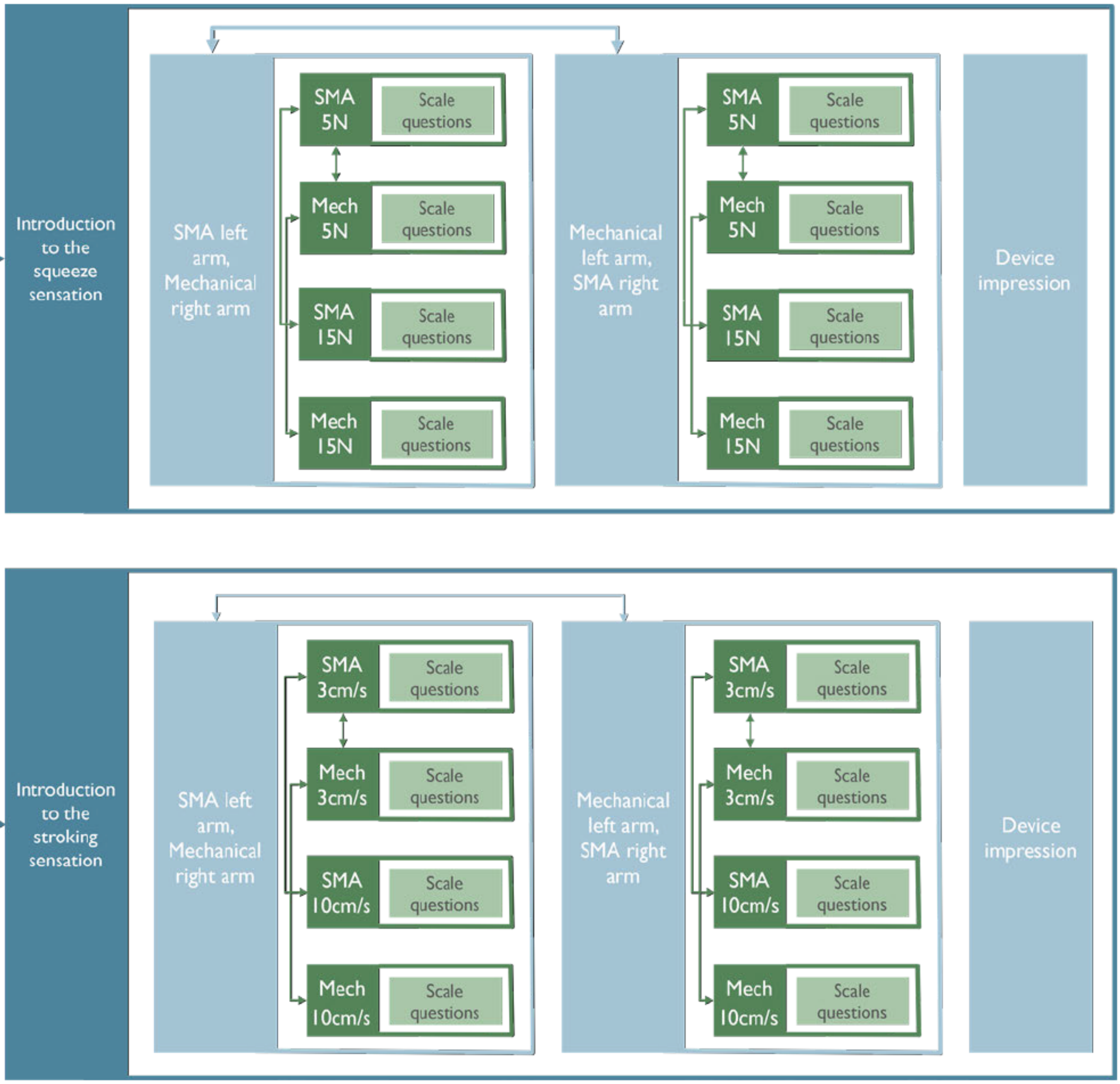


Figure 42 - Structure of the user tests

Participants

There were 22 participants involved in the user tests, including eighteen women and four men. The age range of the participants is from 23 to 62, with the majority of participants being young adults in their 20s.

Results

The results of the user test will be discussed per subsection of the test. Starting with the information gathered from the introduction to the sensation subsection, which is processed using a thematic analysis. Secondly, the results of the semantic differential scale questions are discussed and analysed using several statistical tests. Finally, the results regarding the device impression are presented and processed so they can be used in the radar chart.

Results introduction to the sensation

A thematic analysis was used to analyse the answers gathered through the open question during the introduction to the sensation. First, the most relevant words and short phrases were extracted from the full responses. Using this method, the essential meaning of participants' statements was captured, hence enabling clear and concise categorization of recurring themes. The categorization was done separately for each sensation per actuation method. The analysis began with an inductive approach, lightly guided by the questions posed to participants, allowing meaningful themes to develop from the data without a predetermined framework. Once key patterns were identified, a deductive approach was applied to achieve similar structures across the different sensation and actuation methods, to enable easy comparison. The five overarching themes identified are: effect of the sensation, perceived intention, movement, similarities, and actuator consequences. The thematic analysis is found in Appendix F.

Effect of the sensation

The effect of the sensation created by the SMA-actuated squeezing device, most frequently mentioned by participants, was feeling safe and comforted. However, the feeling of surprise was also mentioned several times, and in some cases, even slightly annoying. One participant mentioned: "The feeling of security, safety. I'm here, it's okay" whilst another said: "That felt weird, it surprised me". Contrastingly, the mechanically actuated squeeze device had a sensation effect that created a sense of urgency in the participants, often mentioning a feeling of shock or surprise. One participant expressed: "it almost gives me a stressed feeling, it's an urgency squeeze." When comparing the squeeze sensations, one participant summarized: "The mechanically actuated device felt more urgent, SMA actuation felt more like, no worries, take your time."

The SMA-actuated stroking device had a sensation effect that made participants happy and curious, the sensation also made participants feel tickled. One participant described: "It tickles, and makes me laugh, so a happy or amusing feeling", and another said: "It makes me very curious, nice feeling though". Similarly, the effect of the sensation created by the mechanical stroking device on the participants mainly mentioned feeling tickled, however, it also included attention-grabbing. One participant said: "I feel a lot more aware, more alert".

In Figure 43, a generalized overview of the terms used to describe the effect of the sensation for each device is shown.

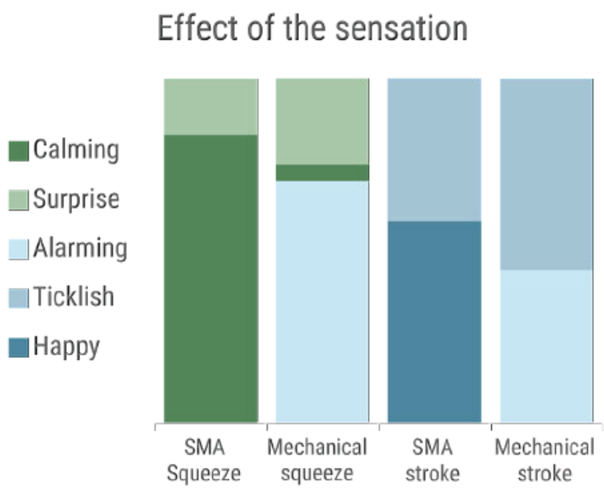


Figure 43 – A generalized overview of the effect of the sensation descriptors

Perceived intention

Participants described the perceived intention of the sensation created by the SMA actuated squeeze device as calming, gentle and comforting. One participant described: “maybe someone wrapping their arm around the wrist, firm but gentle grab,” and another participant said: “It was a gentle feeling, quiet, a squeezing sensation but very subtle”. Opposingly, the perceived intention of mechanical squeeze sensation interpreted by the participants included worry, aggression and stress. With one participant saying: “It seems more aggressive, but doesn't hurt.” The distinction between the two squeeze devices was clearly expressed by one participant, who remarked: “SMA actuated device was softer, tender and more pleasant, the mechanical actuation was more aggressive, I think because the SMA actuation had a build-up and the mechanical actuation was a short sensation”.

The perceived intention of the SMA-actuated stroking sensation was identified as sweet and soft, however, it was also mentioned several times that the sensation felt cut off or accidental. As one participant described it: “Like accidentally sweeping past a person, to swoosh past them and then accidentally touching them anyway.” The mechanical stroking device had a perceived intention by the sensation of being both relaxed and gentle as well as obligatory and annoying, experienced by the participants. A participant described: “A comforting stroke, it feels nice, relaxed,”

In Figure 44, a generalized overview of the terms used to describe the perceived intention of the sensation for each device is shown.

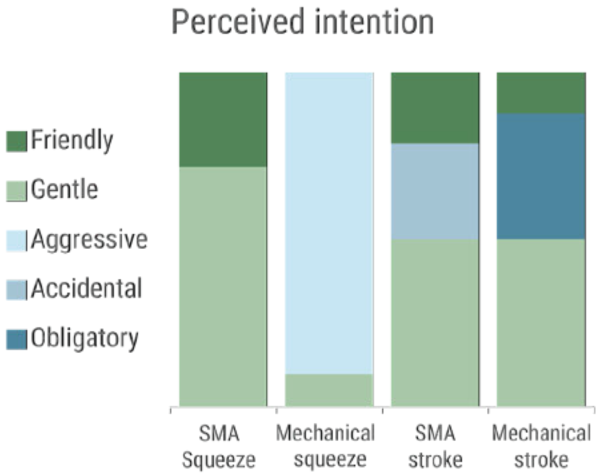


Figure 44 – A generalized overview of the perceived intention descriptors

Movement

The movement of the SMA-actuated squeeze device was described as being slower and gradual, almost in slow motion, by the participants. One participant said: “Like someone grabbing you, but in slow motion”. In contrast, the movement of the mechanical squeeze device was described as quick and strong. One participant said: “Wow, that scared me, it was really quick, in one really strong movement”. A participant compared the sensations, describing them: “SMA actuation is a smoother, gradual progression, mechanical actuation moves very suddenly, abruptly.”

The movement of the SMA-actuated stroking device was described as smooth and predictable, whilst the mechanically actuated stroke was experienced as weird and jerky. One participant described it: “The SMA actuated device was quite predictable, and the mechanical actuation felt more random in its movement and direction.”

In Figure 45 , a generalized overview of the terms used to describe the movement for each device is shown.

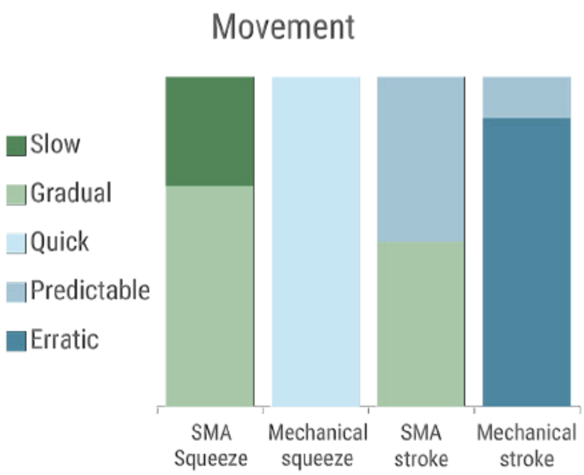


Figure 45 - A generalized overview of the movement descriptors

Similarities

Similarities to the SMA actuated squeeze sensation identified by the participant often mentioned a humanlike sensation, as well as comparing it to an elastic or inflating band. One participant said: "Like a light touch of a human being," whilst another participant said: "Like a hair elastic that's just a little too tight and then removing it". For the mechanical squeeze device, similarities mentioned were a blood measuring band or an aggressive grab by someone. One participant mentioned: "Like an inflatable cuff measuring blood pressure, but smaller and quicker", with another participant saying: "As if suddenly grabbed against your will." It was also often mentioned that the sensation felt artificial, strange, or robotic.

When finding similarities to the SMA actuated stroking sensation, the participant mentioned human touch several times, other comparisons included a feather, brush, or insect moving along the arm. One participant mentioned: "Feels like a little thumb massage." However, some participants also found the sensation confusing or unfamiliar. The mechanical stroking sensation was compared by the participants to sensations with multiple stimuli, such as blades of grass and flowers. As one participant put it: "Moving with your hands through a field of soft flowers." Comparing the sensation to human touch was done sparingly.

In Figure 46 , a generalized overview of the similarities to the sensations the participants named for each device is shown.

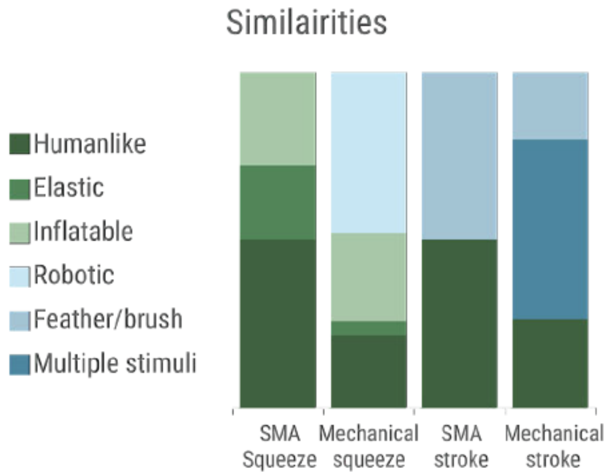


Figure 46 - A generalized overview of the similarities mentioned

Actuator consequences

The SMA-actuated squeeze device received comments on the heat that was radiating from the SMA wire. One participant expressed: "It feels pleasant, calming. It gets warm in a nice way." In contrast, the created noise by the mechanical squeeze device received more negative comments. As one participant who got scared by the noise said: "It was more artificial, the noise is horrible, less organic."

For the mechanical stroking device, the created vibration was mentioned highly frequently. Participants compared the sensation to a vibrating phone, with one participant even mentioning: "I feel the vibration nearly more than the stroking sensation."

Results semantic differential scale questions

The results of the semantic differential scale questions from the user test are found in Appendix G. To analyse the results for each variable, a repeated measures ANOVA was conducted, comparing the actuation method and the actual force of the squeeze. Based on the results of this statistical test, the relevant paired comparison tests are conducted, either using the paired samples t-test or the Wilcoxon signed-rank test. For each variable, the normality is checked using the Shapiro-Wilk test. If this showed that the data is not normally distributed ($p < 0.05$), the Wilcoxon signed-rank test was used instead of the standard paired samples t-test. The significance level was corrected by dividing the typical significance of $p = 0.05$ by the number of conducted t-tests.
All statistical test results are included in Appendix H. To enable easier readability in the text, the short format of just the p value is used; the complete statistical format is given in the table below each section of text.

Squeeze sensation

For each variable, the statistical tests are conducted as described above. The following results regard the experience of the squeeze sensation.

Pleasantness

The repeated measures ANOVA conducted on the pleasantness results showed a significant effect for the actuation method ($p = 0.002$). The effect of the actual force ($p = 0.267$) and the interaction between the two ($p = 0.228$) were not significant. In Table 6, the results are displayed, and in Figure 47, they are visualized.

Actuation method	$F(1,21) = 13.037$, $p = 0.002$, $\omega^2 = 0.175$
Varying force	$F(1,21) = 1.298$, $p = 0.267$, $\omega^2 = 0.005$
Actuation & force interaction	$F(1,21) = 1.543$, $p = 0.228$, $\omega^2 = 0.005$

Table 6 - Results of the repeated measures ANOVA conducted on the pleasantness ratings

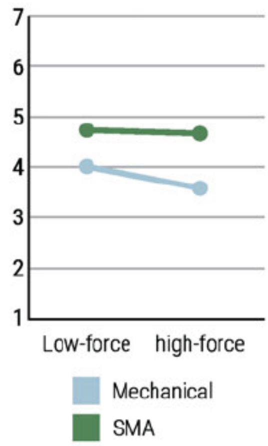


Figure 47 – Repeated measures ANOVA results conducted on the pleasantness visualized

Based on the significant results from the repeated measures ANOVA, three paired comparison tests were conducted. All comparisons are normally distributed according to the Shapiro-Wilk test, therefore, paired samples t-tests were done using a corrected significance level of 0.017. Pleasantness ratings were significantly higher for SMA actuation compared to mechanical actuation across all conditions. This effect was observed in the overall comparison ($p = 0.002$), as well as for both the high-force ($p = 0.003$) and low-force conditions ($p = 0.010$). In Table 7, the results of the conducted paired samples t-tests between the electromechanical and SMA actuation are shown, in Figure 48, these results are visualized.

Between actuation comparison:

General	$t(21) = 3.611$, $p = 0.002$
High-force	$t(21) = 3.362$, $p = 0.003$
Low-force	$t(21) = 2.820$, $p = 0.010$

Table 7 - Results of the paired samples t-tests conducted on the pleasantness ratings

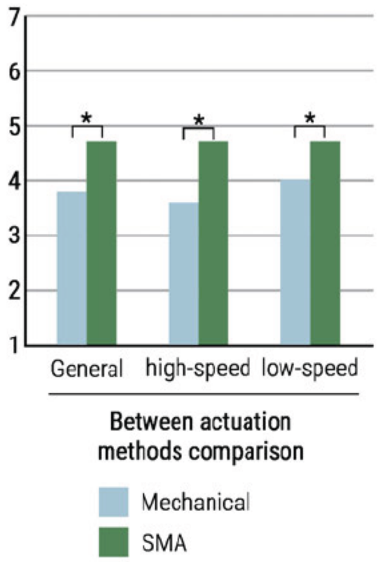


Figure 48 - Results of the repeated measures ANOVA conducted on the pleasantness visualized
** p < 0.017*

Perceived force

A Pearson correlation was conducted between intensity and perceived force. The result revealed a very strong positive correlation ($r = 0.857$, $p < 0.001$), indicating that the two variables nearly capture identical information. The results from both the repeated measures ANOVA and paired samples t-tests conducted on intensity and perceived force were consistent, showing no significant differences in outcomes. Given the high correlation between the two variables, this redundancy justifies the exclusion of intensity from following analyses of the squeezing sensation. As the perceived force sufficiently captures the relevant information, this variable is selected to focus on for the remainder of the analysis.

The repeated measures ANOVA showed significant main effects for actuation ($p < 0.001$) and actual speed ($p < 0.001$). There was a statistically significant interaction between the effects of the actuation method and actual force on the perceived force ($p < 0.001$). In Table 8, the results are displayed, and in Figure 49, they are visualized.

Actuation method	$F(1,21) = 46.958$, $p < 0.001$, $\omega^2 = 0.399$
Varying force	$F(1,21) = 42.633$, $p < 0.001$, $\omega^2 = 0.396$
Actuation & force interaction	$F(1,21) = 32.267$, $p < 0.001$, $\omega^2 = 0.275$

Table 8 - Results of the repeated measure ANOVA conducted on the perceived force ratings

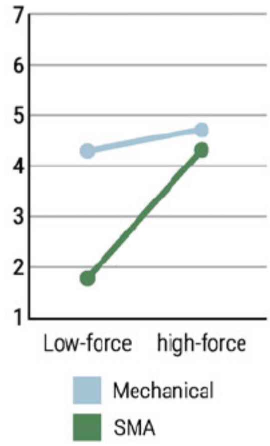


Figure 49 - Results of the repeated measures ANOVA conducted on the perceived force visualized

Based on the significant results from the repeated measures ANOVA, five paired samples t-tests were conducted since all comparisons are normally distributed, a corrected significance level of 0.01 is used. The first t-test revealed that the perceived force ratings for mechanical actuation were significantly higher than for SMA actuation, $p < 0.001$. When comparing the force results of the mechanical device exerting high force to those of the SMA device exerting high force, the difference is not significant ($p = 0.211$). However, a very significant difference was found comparing the low-force sensations from the two actuation methods ($p < 0.001$). Additionally, a great significant difference was found between the low-force and high-force sensations of the SMA actuated device, with the high-force sensation being perceived as more force ($p < 0.001$). The force of the low- and high-force sensation of the mechanically actuated device was not perceived significantly different ($p = 0.193$). In table 9, the results are displayed and in Figure 50, they are visualized.

Between actuation comparison:	
General	$t(21) = 6.853$, $p < 0.001$
High-force	$t(21) = 1.290$, $p = 0.211$
Low-force	$t(21) = 9.574$, $p < 0.001$
Within actuation comparison:	
Mechanical	$t(21) = 1.344$, $p = 0.193$
SMA	$t(21) = 9.070$, $p < 0.001$

Table 9 - Results of the paired samples t-tests conducted on the perceived force ratings

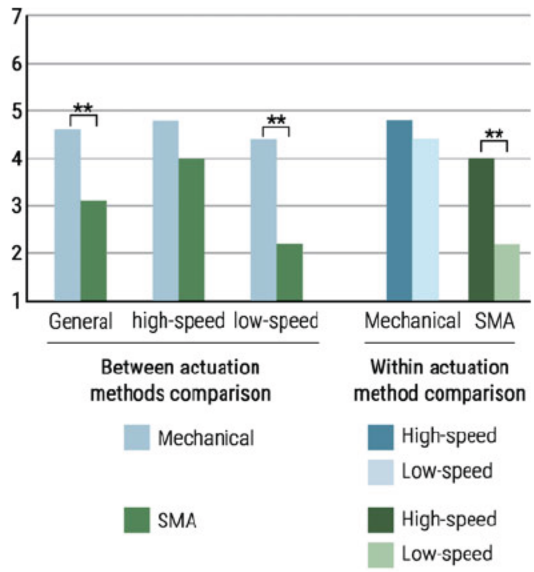


Figure 50 - Results of the paired samples t-tests conducted on the perceived force visualized
*** p < 0.01*

Humanlikeness

The repeated measures ANOVA conducted on the Humanlikeness results showed a significant effect by the actuation method ($p = 0.002$). No significant effect was identified for the varying force ($p = 0.409$), nor did it show a significant effect by the interaction between the two ($p = 0.057$). In table 10, the results are displayed and in Figure 51, they are visualized.

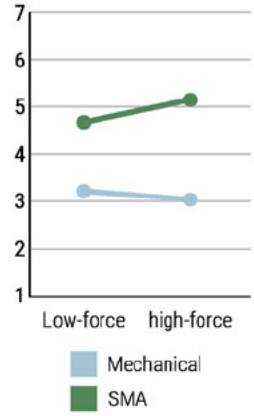


Figure 51 - Results of the repeated measures ANOVA conducted on the humanlikeness ratings visualized

Actuation method	$F(1,21) = 12.266, p = 0.002, \omega^2 = 0.277$
Varying force	$F(1,21) = 0.711, p = 0.409, \omega^2 = 0.000$
Actuation & force interaction	$F(1,21) = 4.059, p = 0.057, \omega^2 = 0.030$

Table 10 - Results of the repeated measures ANOVA conducted on the humanlikeness ratings

Based on these results, three direct comparisons were conducted, using a corrected significance level of 0.017. The Shapiro-Wilk test showed a normal distribution for the high-force sensations ($W = 0.0914, p = 0.056$) and not normal distributions for the overall comparison ($W = 0.892, p = 0.020$) nor the low-force sensations ($W = 0.864, p = 0.006$).

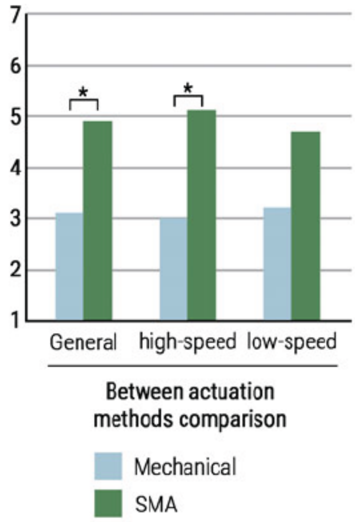


Figure 52 - Results of the direct comparisons tests conducted on the humanlikeness ratings visualized
** p < 0.017*

The Wilcoxon signed-rank test showed a significant difference in the overall comparison ($p = 0.002$), with the SMA actuation scoring higher than the mechanical actuation. The paired-samples t-test comparing the high-force sensations ($p < 0.001$) showed a significant difference between the actuation methods, with again SMA actuation being perceived as more humanlike. As for the low-force sensations, no significant difference ($p = 0.036$) was identified between the actuation methods. In table 11, the results are displayed and in Figure 52, they are visualized.

Between actuation comparison:

General	$W = 27.50, p = 0.002$
High-force	$t(21) = 4.782, p < 0.001$
Low-force	$W = 61.5, p = 0.036$

Table 11 - Results of the paired comparison tests conducted on the humanlikeness ratings

Feeling

The repeated measures ANOVA showed a significant effect by the actuation method ($p < 0.001$) as well as a significant main effect of the varying force ($p = 0.015$). The interaction effect was not significant ($p = 0.829$). In table 12, the results are displayed and in Figure 53, they are visualized.

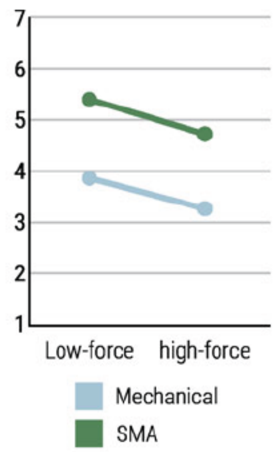


Figure 53 - Results of the repeated measures ANOVA conducted on the feeling ratings visualized

Actuation method	$F(1,21) = 34.345, p < 0.001, \omega 2 = 0.461$
Varying force	$F(1,21) = 6.949, p = 0.015, \omega 2 = 0.126$
Actuation & force interaction	$F(1,21) = 0.048, p = 0.829, \omega 2 = 0.000$

Table 12 - Results of the repeated measure ANOVA conducted on the feeling ratings

The Shapiro-Wilk test indicated that all comparisons are normally distributed, apart from the comparison of the low-force sensations across the different actuation methods. Therefore, four paired-sample t-tests and one Wilcoxon signed-rank test were conducted, using a corrected significant level of 0.01.

Friendliness ratings were significantly higher for SMA actuation compared to Mechanical actuation across all conditions. This effect was observed in the overall comparison (< 0.001), as well as for both the high-force ($p < 0.001$) and low-force conditions ($p < 0.001$). When comparing the high-force sensation to the low-force sensation from the mechanically actuated device, significant differences are identified ($p = 0.009$) with the lower-force sensation being perceived as more friendly. Between the varying forces by the SMA actuated device no significant difference was found ($p = 0.070$). In table 13, the results are displayed and in Figure 54, they are visualized.

Between actuation comparison:	
General	$t(21) = 5.860, p < 0.001$
High-force	$t(21) = 4.716, p < 0.001$
Low-force	$W = 12.0, p < 0.001$
Within actuation comparison:	
Mechanical	$t(21) = 2.890, p = 0.009$
SMA	$t(21) = 1.907, p = 0.070$

Table 13 - Results of the paired comparison tests conducted on the feeling ratings

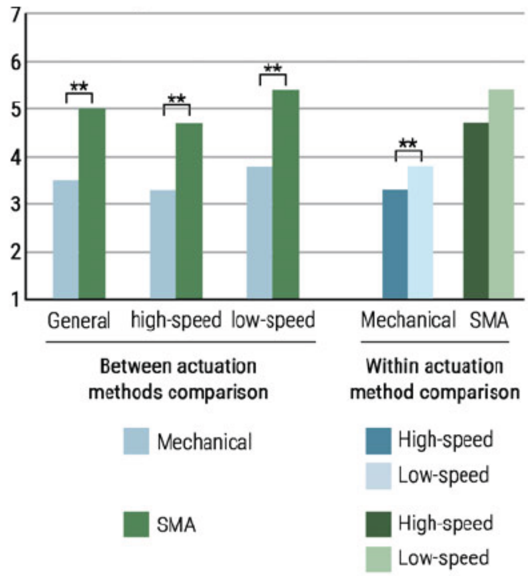


Figure 54 - Results of the direct comparisons tests conducted on the feeling visualized
*** p < 0.01*

Stroking sensation

For each variable, the statistical tests are conducted as described previously. The following results regard the experience of the stroking sensation.

Pleasantness

The repeated measures ANOVA conducted on the pleasantness scores from the stroking devices showed a significant main effect of the actuation methods ($p < 0.001$), as well as the varying speed ($p = 0.039$). There appeared no significant interaction effect ($p = 0.184$). In table 14, the results are displayed and in Figure 55, they are visualized.

Actuation method	$F(1,21) = 23.801, p < 0.001, \omega 2 = 0.262$
Varying force	$F(1,21) = 4.825, p = 0.039, \omega 2 = 0.039$
Actuation & force interaction	$F(1,21) = 1.888, p = 0.184, \omega 2 = 0.005$

Table 14 - Results of the repeated measures ANOVA conducted on the pleasantness ratings

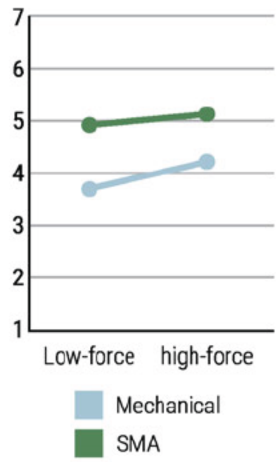


Figure 55 - Results of the repeated measures ANOVA conducted on the pleasantness visualized

Based on these results and the results of the Shapiro-Wilk test showing that all comparisons are normally distributed, five paired samples t-tests were conducted. The significance level was adjusted to 0.01.

Across all conditions that compare different actuation methods, pleasantness ratings were higher for SMA actuation than the mechanical actuation. The general comparison of SMA to mechanical actuation showing significant difference ($p < 0.001$), as well as for both the high-speed ($p < 0.001$) and low-speed conditions ($p < 0.001$). When comparing the low-speed and high-speed variations within each actuation method, no significant differences are found. In table 15, the results are displayed and in Figure 56, they are visualized.

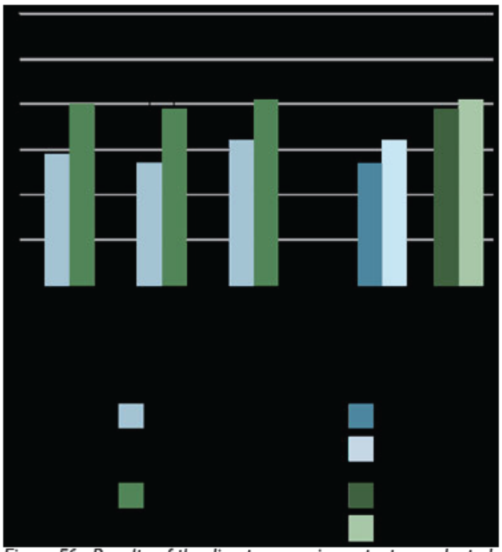


Figure 56 - Results of the direct comparisons tests conducted on the pleasantness visualized
*** p < 0.01*

Between actuation comparison:	
General	$t(21) = 4.879, p < 0.001$
High-force	$t(21) = 4.405, p < 0.001$
Low-force	$t(21) = 4.283, p < 0.001$
Within actuation comparison:	
Mechanical	$t(21) = 2.215, p = 0.038$
SMA	$t(21) = 1.278, p = 0.215$

Table 15 - Results of the paired samples t-tests conducted on the pleasantness ratings

Intensity

The repeated measures ANOVA conducted on the intensity results showed a significant main effect of the actuation method ($p = 0.001$). No significant main effect of the varying speed ($p = 0.110$) or the interaction effect are identified ($p = 0.470$). In Table 16, the results are displayed and in Figure 57, they are visualized.

Actuation method	$F(1,21) = 14.433, p = 0.001, \omega 2 = 0.161$
Varying force	$F(1,21) = 2.789, p = 0.110, \omega 2 = 0.032$
Actuation & force interaction	$F(1,21) = 0.542, p = 0.470, \omega 2 = 0.00$

Table 16 - Results of the repeated measures ANOVA conducted on the intensity ratings

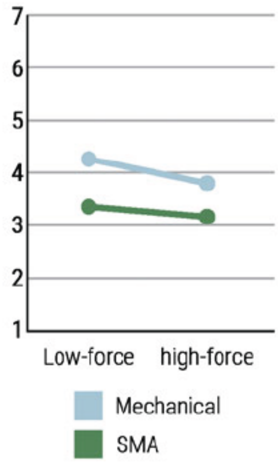


Figure 57 - Results of the repeated measures ANOVA conducted on the intensity visualized

The Shapiro-Wilk test of Normality shows that all combinations are normally distributed, therefore, three paired-samples t-tests are conducted using $p = 0.017$ as the corrected significance level. The mechanical actuation is perceived as more intense than the SMA actuation in all conditions. In table 17, the results are displayed and in Figure 58, they are visualized.

Between actuation comparison:

General	$t(21) = 3.799$, $p = 0.001$
High-force	$t(21) = 2.782$, $p = 0.011$
Low-force	$t(21) = 3.014$, $p = 0.007$

Table 17 - Results of the paired samples t-tests conducted on the intensity ratings

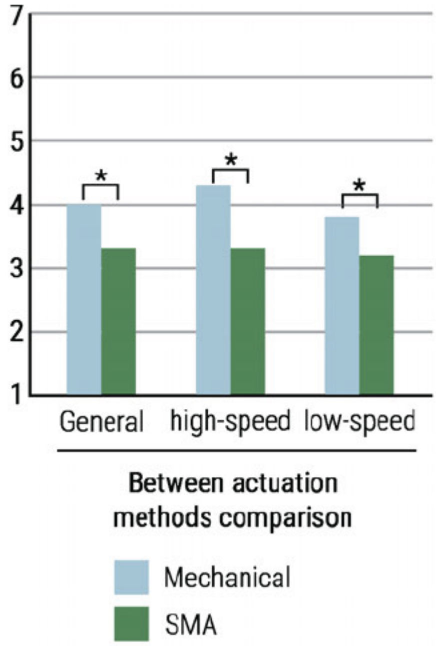


Figure 58 - Results of the direct comparisons tests conducted on the intensity visualized
** p < 0.017*

Humanlikeness

From the repeated measures ANOVA resulted a significant main effect of actuation method ($p < 0.001$). No significant main effect of varying speed ($p = 0.557$) or interaction effect ($p = 0.419$) was determined. In table 18, the results are displayed and in Figure 59, they are visualized.

Actuation method	$F(1,21) = 36.525$, $p < 0.001$, $\omega 2 = 0.435$
Varying force	$F(1,21) = 0.356$, $p = 0.557$, $\omega 2 = 0.00$
Actuation & force interaction	$F(1,21) = 0.680$, $p = 0.419$, $\omega 2 = 0.00$

Table 18 - Results of the repeated measures ANOVA conducted on the humanlikeness ratings

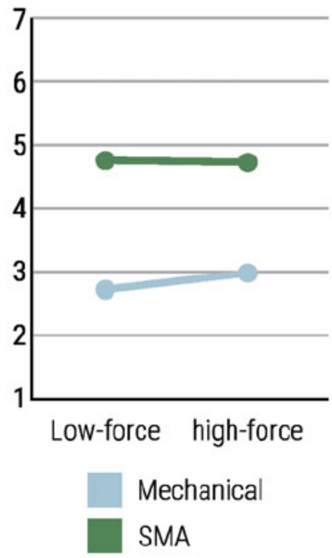


Figure 59 - Results of the repeated measures ANOVA conducted on the humanlikeness visualized

Based on these results, three paired comparison tests are conducted. Shapiro-Wilk tests showed normal distribution for all combinations, so paired samples t-tests are conducted with 0.017 as the corrected significance level. All combinations showed very high significance ($p < 0.001$) with SMA being perceived as more humanlike than the mechanically actuated stroking device. In table 19, the results are displayed and in Figure 60, they are visualized.

Between actuation comparison:

General	$t(21) = 6.044, p < 0.001$
High-force	$t(21) = 5.649, p < 0.001$
Low-force	$t(21) = 4.819, p < 0.001$

Table 19 - Results of the paired samples t-tests conducted on the humanlikeness ratings

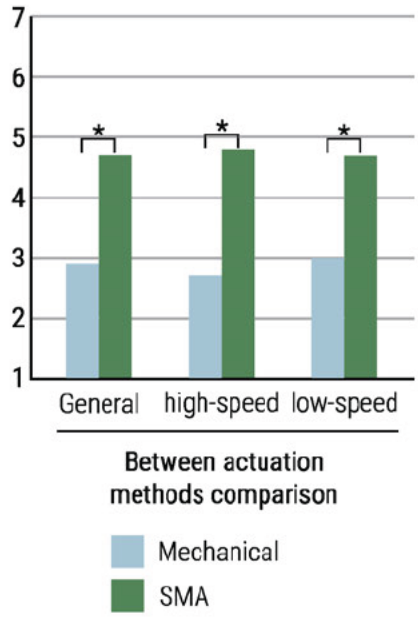


Figure 60 - Results of the direct comparisons tests conducted on the humanlikeness visualized
** p < 0.017*

Perceived speed

The repeated measures ANOVA conducted on the results of perceived speed showed a significant main effect of the actuation method ($p = 0.045$), as well as the main effect of varying speed ($p < 0.001$). Additionally, an interaction effect was determined to be significant ($p = 0.034$). In table 20, the results are displayed and in Figure 61, they are visualized.

Actuation method	$F(1,21) = 4.531, p = 0.045, \omega2 = 0.089$
Varying force	$F(1,21) = 33.584, p < 0.001, \omega2 = 0.249$
Actuation & force interaction	$F(1,21) = 5.170, p = 0.034, \omega2 = 0.055$

Table 20 - Results of the repeated measures ANOVA conducted on the perceived speed ratings

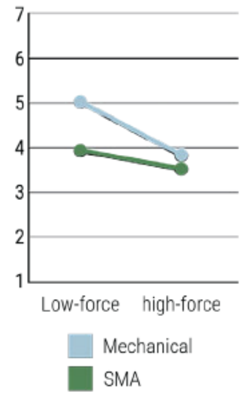


Figure 61 - Results of the repeated measures ANOVA conducted on the perceived speed visualized

All comparisons are normally distributed, therefore, five paired samples t-tests were conducted using 0.01 as the significance level. The general comparison between SMA actuation with the mechanical actuation showed no significant difference ($p = 0.045$). However, comparing the actuation methods for the high-speed condition showed significance ($p = 0.006$). Additionally, the mechanically high-speed sensation compared to the low-speed sensation showed high significance ($p < 0.001$). The difference between low-speed conditions of the actuation methods showed no significance ($p = 0.437$) and neither did the SMA actuated high-speed sensation compared to the low-speed sensation ($p = 0.028$). In table 21, the results are displayed and in Figure 62, they are visualized.

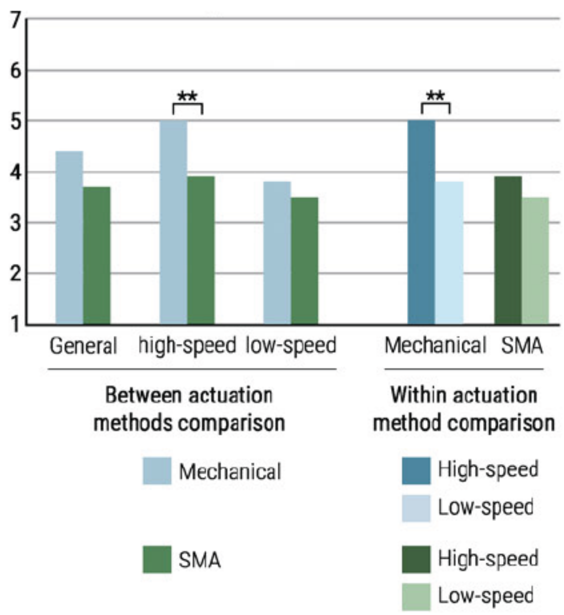


Figure 62 - Results of the direct comparisons tests conducted on the intensity visualized
*** p < 0.01*

Between actuation comparison:	
General	t(21) = 2.129, p = 0.045
High-force	t(21) = 3.037, p = 0.006
Low-force	t(21) = 0.792, p = 0.437
Within actuation comparison:	
Mechanical	t(21) = 4.617, p < 0.001
SMA	t(21) = 2.365, p = 0.028

Table 21 - Results of the paired samples t-tests conducted on the perceived speed ratings

Feeling

The repeated measures ANOVA conducted on the results regarding the underlying feeling, mean or friendly, showed significant main effect of the actuation method ($p < 0.001$) as well as the varying speed ($p = 0.001$), but showed no significant interaction effect ($p = 0.139$). In table 22, the results are displayed and in Figure 63, they are visualized.

Actuation method	F(1,21) = 19.657, p < 0.001, ω2 = 0.224
Varying force	F(1,21) = 14.583, p = 0.001, ω2 = 0.089
Actuation & force interaction	F(1,21) = 2.366, p = 0.139, ω2 = 0.009

Table 22 - Results of the repeated measures ANOVA conducted on the feeling ratings

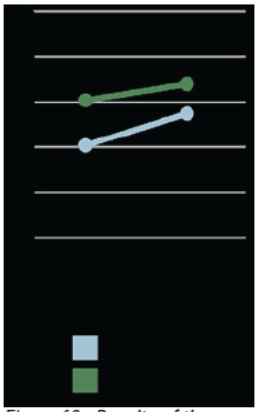


Figure 63 - Results of the repeated measures ANOVA conducted on the feeling visualized

Five paired comparison tests were conducted, Shapiro-Wilk tests showed that only the comparison between the high-speed sensation and the low-speed sensation of the SMA device is not normally distributed ($W = 0.907$, $p = 0.042$). Therefore, four paired-samples t-tests and one Wilcoxon signed-rank test are conducted. A significance level of 0.01 is used.

The SMA actuation is perceived significantly more friendly than the mechanical actuation in the general comparison ($p < 0.001$), the high-speed condition ($p < 0.001$) and the low-speed condition ($p < 0.001$). When comparing the high-speed sensation to the low-speed sensation of the mechanically actuated device, again a significant difference is found ($p = 0.001$). For the comparison between high-speed sensation and the low-speed sensation of the SMA actuation, no significant difference was found ($p = 0.034$). In table 23, the results are displayed and in Figure 64, they are visualized.

Between actuation comparison:	
General	t(21 = 4.434, p < 0.001
High-force	t(21) = 3.892, p < 0.001
Low-force	t(21) = 3.900, p < 0.001
Within actuation comparison:	
Mechanical	t(21) = 3.691, p = 0.001
SMA	W = 23.00, p = 0.034

Table 23 - Results of the paired comparison tests conducted on the feeling ratings

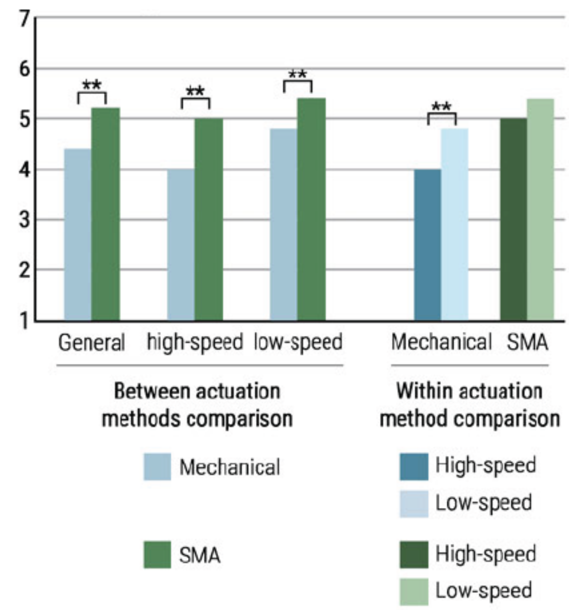


Figure 64 - Results of the direct comparisons tests conducted on the feeling visualized
*** p < 0.01*

Results device impressions

In Appendix I, the results from the user test regarding the experience of wearing the devices are found. These results are used to complete the radar chart for each device.

The results gathered in the user test are used for the user experience metrics in the radar chart. The wearability, impairment and ergonomics metrics were asked directly to participants, but sub-aspects of these metrics were also presented to participants. The final score for each aspect and sub-aspect is calculated with a simple average of all participant scores. To finalize a score per radar chart metric, a weighted average was taken. In table 24, the used weighted averages are shown. The question directly asking for the opinion of the participant regarding the metric was responsible for half of the final score. The sub-aspects compile the other half using a simple average. The magnitude of the sensation is compiled by calculating the average intensity score given by the participants, for both the low and high-force or speed conditions separately. In table 25, the scores of all user experience metrics per device are presented.

Wearability: $$\frac{\frac{Disruption + emotion + anxiety}{3} + wearability}{2}$$

Impairment: $$\frac{\frac{Movement + weigth + change}{3} + impairment}{2}$$

Ergonomics: $$\frac{\frac{Attachment + harm}{2} + ergonomic}{2}$$

Table 24 - Weighted average calculations for the user experiense metrics

		SMA squeeze device	Mechanical squeeze device	SMA stroking device	Mechanical stroking device
Wearability		5.3	2.8	2.9	3.2
Impairment		5.9	3	2.7	3.6
Ergonomics		6	5.7	4.5	5.0
Magnitude of the sensation	Low	2	4	3	4
	High	4	5	3	4

Table 25 - User experience ratings

Design experience

In the following chapter, the design experience gained during this project is described. This design experience will contribute, together with the device impressions gathered in the user test, to the conclusion regarding the design process perspective. First, the device characteristics of all four wearables are presented via the radar charts, after which the design experience of both actuation methods is discussed.

Device characteristics

The characteristics of final designs of the four haptic devices are presented via the radar charts. The values for the technical and performance metrics are directly derived from the devices, the values for the user experience metrics are obtained from the device impressions section of the user test. The characteristics are first presented in the form of a table, which are then inserted in the radar chart. In the following section, the radar charts representing each haptic device are presented .

SMA actuated squeeze device characteristics

Size	9 cm³	
Weight	10 g	
Controllability	1 aspect	
Degradation	20%	
Wearability	5	
Impairment	6	
Ergonomics	6	
Force	5 N	15 N
Power	10 W	15 W
Power-to-weight	0,5	1
Actuation speed	2,5 s	4 s
Magnitude of the sensation	2	4

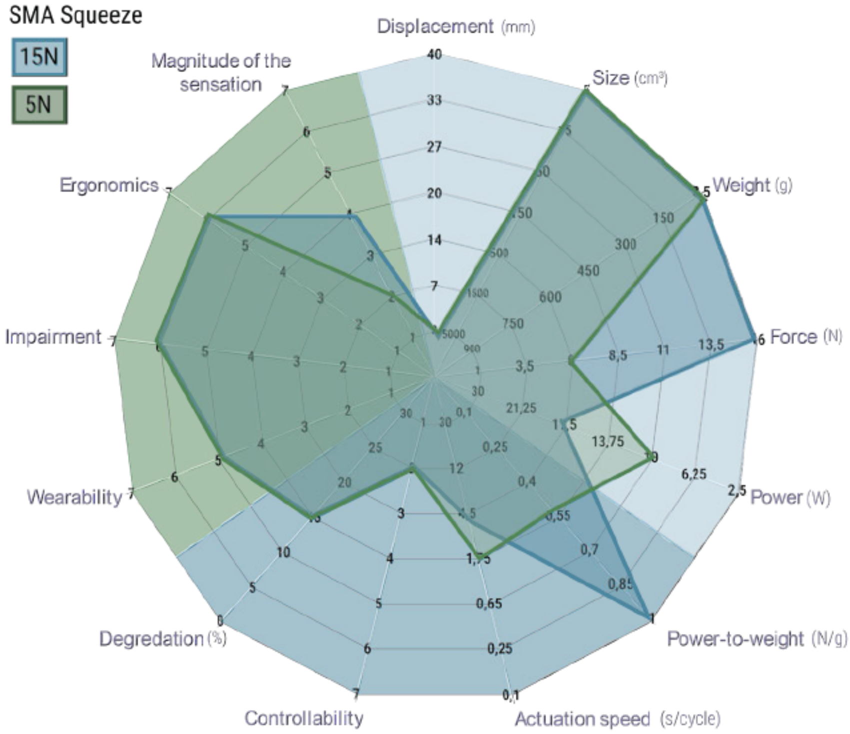


Figure 65 - Radar chart of the SMA-actuated squeeze device

Mechanically actuated squeeze device characteristics

Size	93 cm³	
Weight	40 g	
Power	6,5 W	
Actuation speed	0,3 s	
Controllability	2 aspects	
Degradation	0%	
Wearability	3	
Impairment	4	
Ergonomics	6	
Force	5 N	15 N
Power-to-weight	0,125	0,375
Magnitude of the sensation	4	5

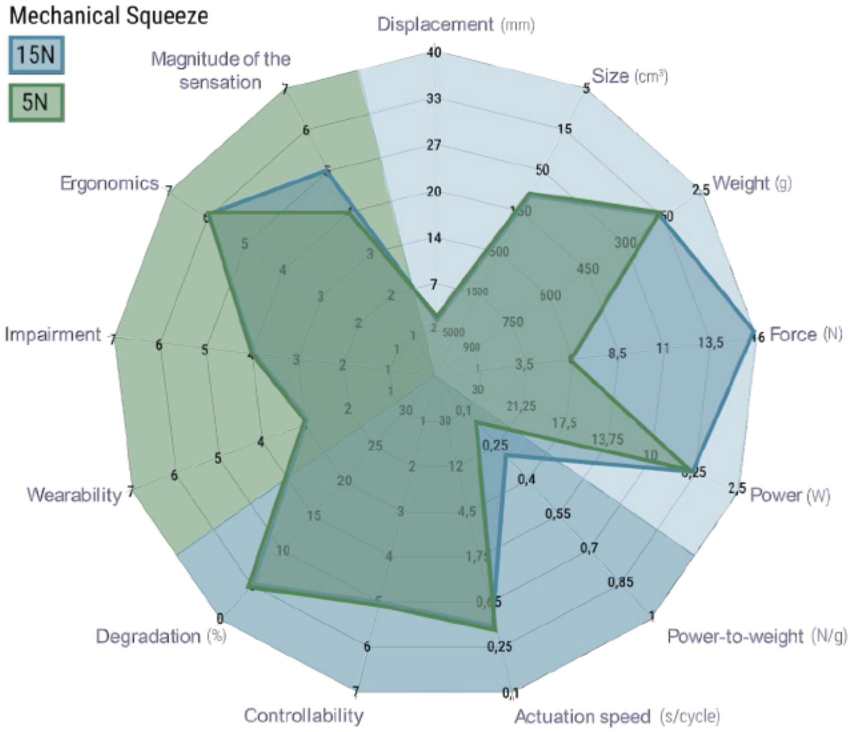


Figure 66 - Radar chart of the mechanically actuated squeeze device

SMA actuated stroking device characteristics

Displacement	2 cm	
Size	32 cm³	
Weight	25 g	
Controllability	1 aspect	
Degradation	30%	
Wearability	3	
Impairment	3	
Ergonomics	4	
Magnitude of the sensation	3	
Actuation speed	10 cm/s	3 cm/s
Power	17 W	12 W

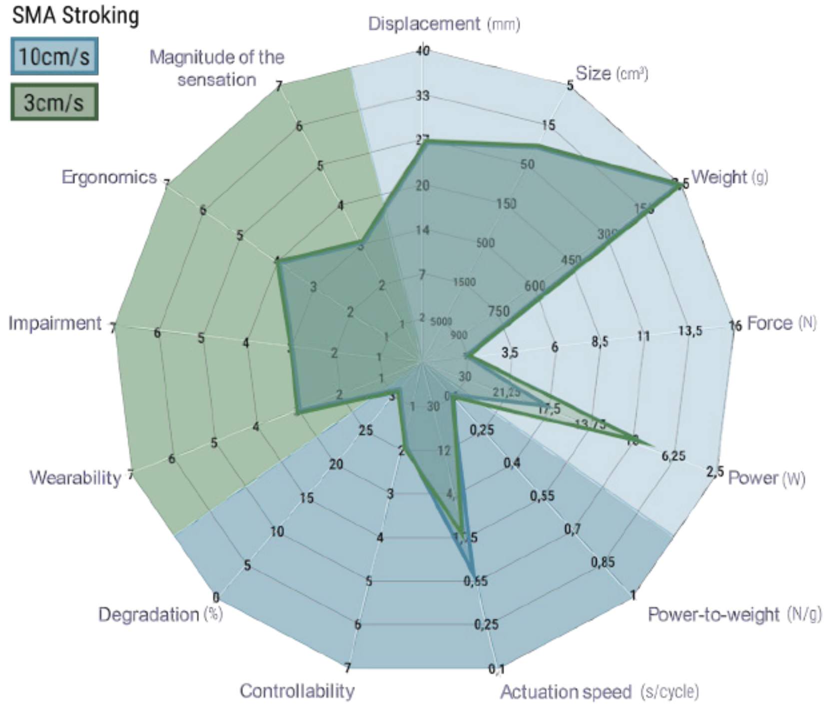


Figure 67 - Radar chart of the SMA-actuated stroking device

Mechanically actuated stroking device characteristics

Displacement	4 cm	
Size	77 cm3	
Weight	55 g	
Power	2,4 W	
Controllability	2 aspects	
Degradation	5%	
Wearability	3	
Impairment	4	
Ergonomics	6	
Actuation speed	10 cm/s	3 cm/s
Magnitude of the sensation	5	4

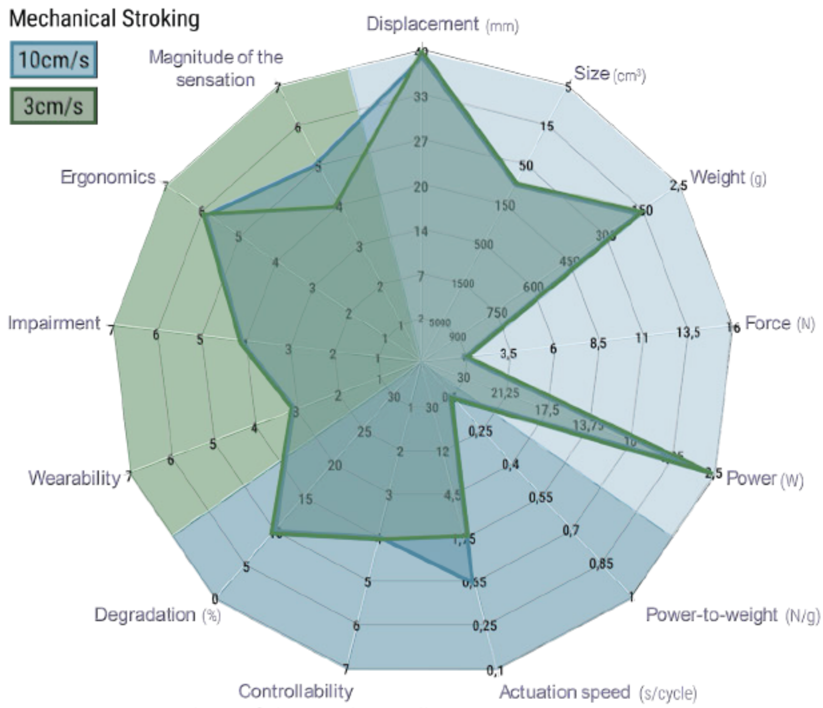


Figure 68 - Radar chart of the mechanically actuated stroking device

Design experience SMA actuation

A great benefit of SMA is their high versatility. However, this also means that there are many ways of applying the wire that are not explored in this project. The following section describes the experience obtained during this project, meaning there is still plenty to explore for future research. When designing devices that create a squeezing and stroking sensation, several challenges were met.

From the stroking device, it became very clear that creating a big displacement is challenging with SMA. The wire is capable of it, but it led to an increase in the volume of the device, as the length of the spring is longer than the actual displacement created. This also influenced the durability of the stroking device, during user testing it became clear that the displacement created was decreasing. Even though the initial displacement achieved was four centimetres, only two centimetres of displacement was achieved after all the tests. Compared to this, the design of the squeeze device, when no big displacement was aimed for, was more straightforward to create, since the SMA wire can be wrapped around the wrist in various shapes to create a squeezing effect easily.

Designing the squeezing device proved that creating high force using SMA is very feasible. The several of the first initial designs did not yet meet the high-force requirements, but by layering SMA wire this was easily resolved. Later when a slight increase was needed the amount of coils was decreased which increased the force, but another option would have been to add a third SMA spring. This shows that even more force than the 15N reached in this project can be achieved if desired.

The squeeze device also showed that the heat created by the wire has to be taken into account.

For this project, accessible SMA wires were used, which had an activation temperature of 50 to 70 degrees Celsius. This is much too high if the wire must be placed close to the skin, therefore, the heat was a big consideration when designing the squeeze device. As demonstrated with the final prototype, there are ways to resolve this, even though this did influence the sensation. This project was limited to accessible wire, however, selecting a wire with lower activation temperature would already mitigate a part of this problem.

Working with shape memory alloy proved that there is always one controllable aspect to some extent. For the squeeze device the force is controlled by the power, and for the stroking device the speed of the movement is controlled by the power. Working with the material proved that the level of control is sufficient and intuitive to work with.

As mentioned, the heating of the wire is controlled by the power used to activate the material. The speed at which this is done directly influences the actuation speed. The cooling time was a slight challenge during the design of the stroking device when using the 1mm thick wire. However, when switching to 0.5 mm wire, this became manageable.

Design experience electromechanical actuation

When working on designs for haptic wearables using classical mechanical actuation, it becomes clear that there are many options available for this. There are many actuators with all kinds of specification available, for this project was determined to make use of easily accessible actuators. Selecting an actuator already in possession for the devices considerably restricted the options when working with electromechanical actuation.

When designing with the mechanical actuation, the process initially seemed more simple and familiar. However, when aiming to achieve certain performance metrics, sometimes unexpected limitations were met. For example, when designing the stroking device finding the actuator providing the exact rotational speed desired became difficult. This was partly caused by a lack of experience and knowledge of working with the actuator. Therefore, when working with mechanical actuators it is of high importance to know precisely the performance needed from the actuator and find one with suitable specifications.
During the user testing the stroking device did not always work properly because of the fit of the device to the participants. Due to differences in wrist and arm sizes, the actuator was sometimes not in contact with the arm of the participant, which caused no feeling of the sensation. However, at other times there was too much force exerted on the end effector which the actuator could not overcome, leading to no movement. By selecting a higher peak torque for the actuator this could be mitigated. Another option could be a redesign, adjusting to avoid this stalling.

Controlling the exact movement of the motor is possible for some types and not others. For example, the servo motor is controlled in steps, whilst for the stepper motor the amount of repeats of actuation is determined, which is not directly linked to a time or distance. So again the selection of the actuator based on the specification is important. However, the control over the movement of the end effector is also influenced by the movement translations done between the output shaft of the actuator and the end effector. When comparing the two devices, the squeeze device can be controlled in more aspects. This is because the speed of the rotation controls how quickly the full sensation is reached, and the degrees of rotation determine the force exerted. Whilst for the stroking sensation the speed of the rotation only controls one aspect completely, which is the speed of the linear movement. The degrees of the rotation also controls the distance moved, however, this is limited by the design of the rack attached to the end effector. This shows that, whilst the control over the actuator can be precise, the movement translation also affects resulting movement adding a layer of complexity to the level of control.

The designing of the squeeze device proved how the desired peak force directly influenced the size of the device. When one servo motor appeared to be unable to provide enough force, a second servo was added. However, with the rigid shape of the actuator, the size of the device was necessary to also increase. Whilst certain design solutions were applied, the increase of the size of the device was unavoidable. This also highlighted the limitations in design freedom regarding the shape of the device. The actuators have predetermined dimensions that must be worked around. The design of the device has to be created around the actuator, whilst focusing on the created sensation might be preferred in the affective haptics field.

Discussion

In the following chapter, the interpretations and implications of the results are discussed. This will be addressed through the two perspectives. Additionally, the limitations of the project and the recommendations for future research are discussed.

Design process perspective

The insights from the design process perspective were gathered from the design experience gained during the project and the radar charts that capture the device characteristics. First, the radar charts are interpreted, after which all insights are used to address the research questions.

Radar chart interpretations

The radar charts visualising the characteristics of the haptic wearables designed during the project enable easy comparison. In the following section is presented what insights were gathered from these charts. The radar charts of the devices using the same actuation method are compared, as well as the devices creating the same sensation.

SMA actuated devices compared

In Figure 69 and 70, the radar charts of the SMA-actuated devices are shown again. These are the same radar charts as shown in Figure 65 and 67.

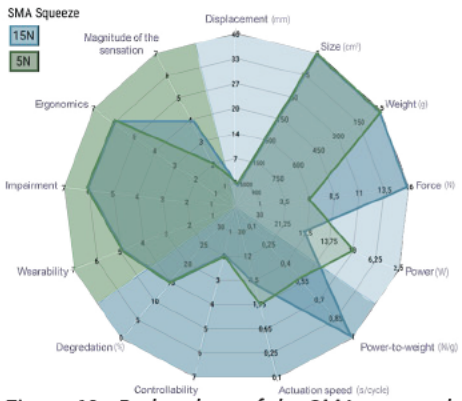


Figure 69 - Radar chart of the SMA-actuated squeeze device

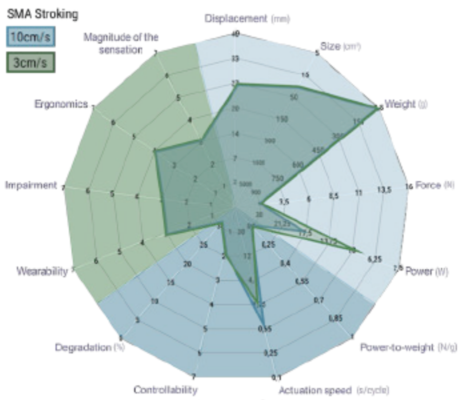


Figure 70 - Radar chart of the SMA-actuated stroking device

First, the radar charts of the SMA-actuated devices were compared with each other. When comparing the radar charts of the devices, it is very noticeable that the stroking device is rated much lower on the user experience metrics compared to the squeeze device. Especially the wearability and the impairment are not rated well, whilst this is the case for the squeeze device. In the baseline comparison, the high versatility of the SMA wire is mentioned as a great advantage. This would explain the lower wearability and impairment scores, since the stroking device did not make use of the ability of the SMA to follow the shape of the body of the user. The material flexibility provides great opportunities regarding these two user experience metrics. However, for the stroking device, this advantage was not made use of, and therefore, the device is not performing as well on these metrics compared to the squeeze device.

The fatigue mentioned in the baseline comparison for the SMA actuation is partially confirmed during this project. Since the performance declined during user testing with the SMA actuated stroking device, fatigue was a challenge in this configuration. On the other hand, the performance of the squeezing SMA actuated device remained as required.

From design experience, it is known that the amount of power used provides controllability over the sensation. In the radar chart of the SMA-actuated device (Figure 69), it is clearly shown how the power increases when a high-force squeeze is created. This is identically found in the radar chart of the stroking device, to create the high-speed stroke sensation, more power is used.

Mechanically actuated devices compared

In Figure 71 and 72, the radar charts of the mechanically actuated devices are shown again. These are the same radar charts as shown in Figure 66 and 68.

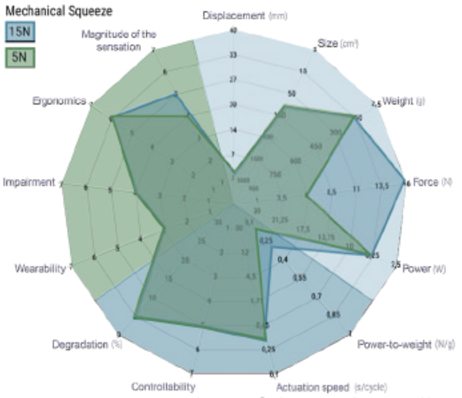


Figure 71 - Radar chart of the mechanically actuated squeeze device

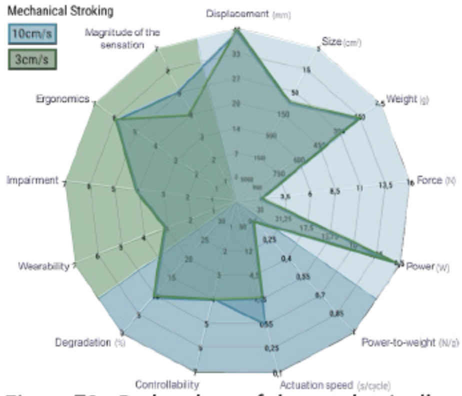


Figure 72 - Radar chart of the mechanically actuated stroking device

When looking at the radar charts regarding the mechanically actuated devices what is most remarkable is that the user experience and the performance metrics in both radar chart are almost scored identically, see Figures X and X. Indicating that whilst the movement of the devices are different, the effect of the actuation method remains similar on the performance and user experience metrics.

Whilst nearly the same, it is noted that the degradation is scored a little bit lower for the stroking device compared to the squeeze device, since more separate components in a device, especially moving ones, will always bring vulnerabilities. The gears in the squeeze device have to withstand forces to exert 15N to the wrist of the user, which is certain to cause wear. However, the stroke device requires more gears to fit together properly, making it even more vulnerable to failure.

Squeeze devices compared

In Figure 73 and 74, the radar charts of the squeeze devices are shown again. These are the same radar charts as Figure 65 and 66.

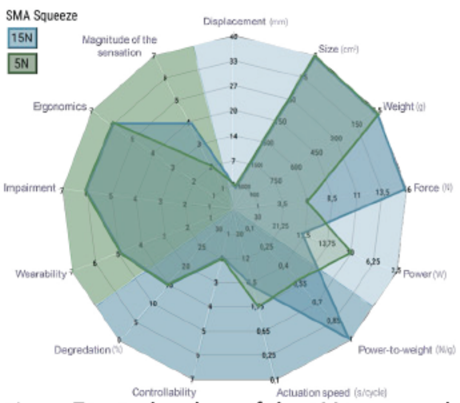


Figure 73 - Radar chart of the SMA-actuated squeeze device

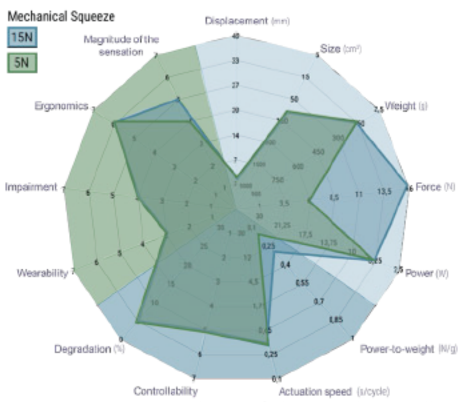


Figure 74 - Radar chart of the mechanically actuated squeeze device

When comparing the squeeze devices, it is most notable that the user experience metrics are rated higher for the SMA actuation, and the mechanically actuated device performs better in most of the performance metrics. One performance metric is an exception to this, which is the power-to-weight metric; this is the only performance metric where the SMA outperforms the mechanical actuation.

In the SMA-actuated squeeze device, it is noticeable that the difference in force influences the power-to-weight ratio. Since this metric relates to force, this outcome is to be expected; however, this relationship is not reflected in the radar chart of the mechanically actuated squeeze device. Since the weight of the mechanically actuated squeeze device is high, the difference in force exerted has little influence on the power-to-weight metric. In the baseline comparison, the weight of the mechanical actuation and the power-to-weight ratio of SMA actuation were also mentioned. These observations from the radar chart support the expectations derived from the literature.

Whilst the power-to-weight ratio scores well when a high-force squeeze is created by the SMA-actuated device, the power also increases with this. This is not the case for the mechanical actuation, the power usage for the mechanical actuation is not different between the force variations. Indicating that the energy efficiency is influenced when a squeeze with different force is exerted when using SMA acutation, whereas it is not affected when using mechancial actuation.

Stroking devices compared

In Figure 75 and 76, the radar charts of the squeeze devices are shown again. These are the same radar charts as Figure 67 and 68.

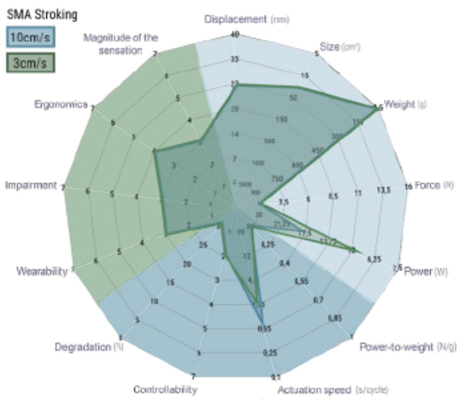


Figure 75 - Radar chart of the SMA-actuated stroking device

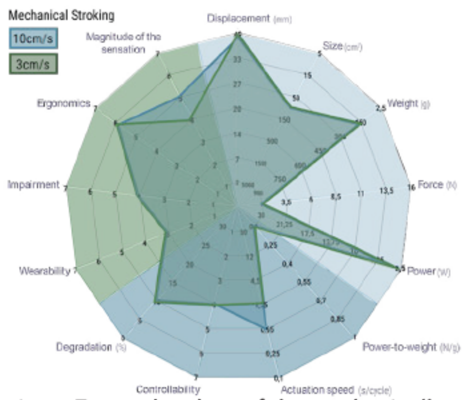


Figure 76 - Radar chart of the mechanically actuated stroking device

When comparing the radar charts of the stroking devices, it can be remarked that the SMA-actuated device performs worse than the mechanically actuated device across nearly all metrics. This reaffirms that creating a big displacement is not suitable for SMA-actuation.

In these radar charts, it is also clearly visualized that the displacement created by the SMA-actuated device ultimately did not reach the required four. This is also reflected in the low score of the degradation metric. The mechanical actuation does not present these difficulties, as the displacement reached four centimetres, and a low amount of degradation appeared.

Finally, it is again shown how the variation in speed in influenced by the power usage of the SMA-actuated device, whilst the power usage stays the same for the mechanically actuated device.

Addressing research questions

In this section, the research questions compiled for the design process perspective are addressed. The previously determined research questions regard metric correlations, advantages and disadvantages and preferred scenarios for each actuation method.

Metric correlations

This section aims to answer the following question: What correlations between evaluation metrics emerge when designing with each actuation method?

For the SMA-actuated devices, it is known that the amount of power used provides controllability over the sensation. This indicates that the power metric is correlated to the metric that requires variable performance when working with SMA actuation.
For SMA actuation, a correlation between the displacement metric and the user experience metrics was indeed found. The design experience proved that creating a big displacement is more challenging, and the radar charts presented a decrease in user experience ratings because of this.

The design experience gained did demonstrated that the movement translations influence the controllability metrics. Additionally, the degradation is influenced by the design of the movement translations in the device.

A final conclusion that can be drawn when comparing all radar charts is that devices creating a big displacement are also bigger in size. Subsequently, the size influences the wearability of the devices. So, requiring a high displacement will most likely lead to decreased wearability.

Advantages and disadvantages

This section aims to answer the following research question: What are the advantages and disadvantages of using either SMAs or electromechanical actuation in haptic wearables?

From the devices creating a squeezing sensation, it can be concluded that the advantages of the classic mechanical actuation are found in controllability and degradation, whilst the disadvantages regard the wearability and the impairment of the device. For the SMA actuation, the opposite conclusion can be drawn. This actuation method provides an advantage when high wearability and/or low impairment are desired. In the baseline comparison the user experience metrics were also mentioned, especially how the SMA actuation would outperform the mechanical actuation in regards to the noise and ergonomics of the device. Whilst the SMA actuation does score better on the user experience metrics in general, the specific mention of the ergonomics metric is not confirmed. However, the noise mentioned in the baseline was confirmed as being a disadvantage during the introduction to the sensation section of the used test.

The biggest disadvantage of SMA actuation identified during this project is creating a big displacement. In addition to being difficult to design, all other metrics suffered when a large displacement was required.

From the design experience, it became apparent that the challenge of mechanical actuation is present in selecting the exact specifications of the actuator. In the baseline comparison, it was mentioned that conventional mechanical actuators are highly controllable. This advantage is found in the precise control over the motor movement, however, precisely controlling the final movement is more difficult. This indicates that the insights from the literature are not entirely confirmed. Especially as, the the degree of control when using an SMA actuator does directly influences the final movement, even tough it cannot be precisely controlled. This provides the advantage of a more intuitive and simple control over the resulting sensation when using SMA actuation.

The rigidity of the conventional mechanical actuation mentioned in the baseline comparison proved to be a disadvantage during the design process, especially when the squeezing device needed a second actuator incorporated. The design of the casing of the device needed to be changed considerably, and the volume of the device increased significantly. This showed how the mechanical actuation has to be created around the actuator, then, after prototyping the complete device, the sensation can be tested. If the sensation is not as desired, the whole device needs to be redesigned and prototyped again. This means that the iterations take more time, posing a disadvantage during the design process. In contrast, when using SMA actuation final movement can be created first, bringing the advantage of being able to design the casing after this is created. The working principle of the sensation can be verified before a complete design needs to be created.

Finally, it is determined that SMA actuation is unable to provide high-frequency repetitions due to the cooling time, while mechanical actuation is capable of doing so. From the baseline comparison this was suspected, yet the heating time delay also mentioned was not experienced as a disadvantage. However, creating multiple sensation in close proximity of each other is an advantage of SMA actuation. Positioning multiple mechanical actuators close to each other is limited to the size of the actuator, whereas this is easily done with SMA.

Preferred scenarios

This section aims to answer the following research question: In which scenarios are either SMAs or electromechanical actuation preferable over the other?

From the previously discussed sections, it can be gathered which scenarios would be suitable for SMA actuation and which would be suitable for conventional mechanical actuation.
The biggest advantage of the SMA actuation is its flexibility. The comparison between the SMA-actuated stroking device and the squeezing device also shows that when not making use of this advantage, the performance of the device will decline. Scenarios where this advantage can be made use of, SMA actuation should definitely be selected. This would include scenarios where the device has to fit the body similarly to the squeeze device.

From comparing all four radar charts, it became clear that the mechanical actuation performs better in high-displacement applications. Therefore, when a bigger movement is necessary for the desired haptic sensation, conventional mechanical actuation is the more suitable option.

If a sensation is desired with high frequency, meaning quick repetitions, mechanical actuation is required. However, when aiming to provide different sensations in close proximity to each other, SMA is suitable since multiple wires are easily combined.
Finally, a scenario where precise control is desired, is suitable for mechanical actuation. If exact distances or durations are required, SMA actuation is not able to guarantee this. Moreover, is it not ensured that the exact same sensation is created when using SMA actuation.

User experience perspective

The insights from the user experience perspective were gathered from the user test, primairly the introduction to the sensation section and the semantic differential questions section. In the following section the interpretations gathered from the statistical tests are presented, after which the compiled research questions regarding the user expeirence are adressed.

User test interpretations

In the following section the significance of the statistical analysis tests ran on the results gathered during the user tests is discussed. In figure 77, the results that showed a significant difference are presented.

In both results regarding the squeezing and the stroking sensations, SMA actuation received higher scores on the pleasantness and humanlikeness of the sensation, regardless of varying force or speed. This indicates that SMA actuation is, in general, perceived as more pleasant and more humanlike than electromechanical actuation.

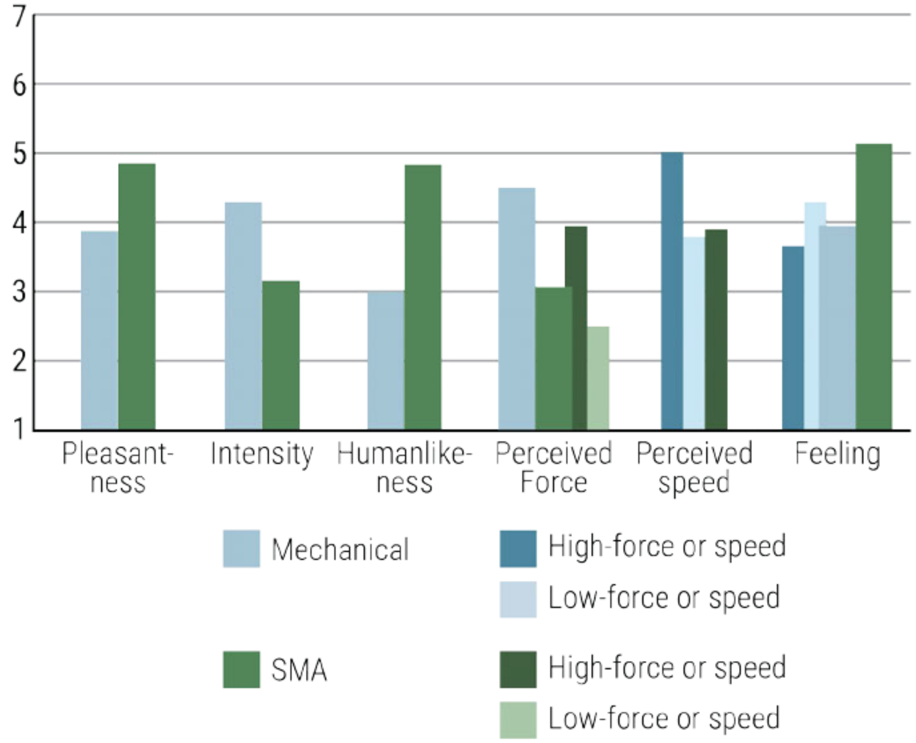


Figure 77 – The combined results with significant differences from the semantic differential scale questions of both the squeezing and stroking sensations.

The results regarding the intensity of the sensation indicate that mechanical actuation is perceived as more intense than SMA actuation. This is consistent in both sensation and again not influenced by the varying force or speed. Moreover, the perceived force of the mechanically actuated squeeze device is always scored high. The comparison within the mechanical actuation between the low-force condition and the high-force condition showed that the participants did not feel a noticeable difference. Whilst there was a difference perceived between the SMA actuated low- and high-force conditions. Contrastingly, the speed perceived in the SMA actuated stroking device was not different for the participant, whilst this difference in speed was noticeable for the mechanically actuated device. These insights indicate that whilst mechanically actuated devices are perceived as stronger, SMA is more suitable if a variation in force is required. However, mechanical actuation appears to allow for more noticeable variation in speed and is perceived as moving faster.

Finally, the participants gave their opinion on whether the sensation felt like a mean or friendly touch. The feeling behind a touch is highly dependent on the context, therefore, the findings based on this question should be considered with some reservations. The results indicate that SMA actuated devices generate sensations that are experienced as more friendly. Variations in force and speed do not have a significant impact on this perception. However, for the mechanically actuated devices, the low-force and speed sensations are perceived as more friendly compared to their high-force and speed variations.

Addressing research questions

The user experience perspective aims to identify the influence of the actuation method on the user experience. In the following section, the enjoyment of the user, the interpretation of the sensation, and preferred scenarios of each actuation method are discussed.

Enjoyment

During the introduction to the sensation each participant commented on the experience of the sensation. When comparing the answers of each actuation method, clear differences were found. The effect of the sensation of the SMA-actuated devices was mostly positive, such as feeling safe or happier, whilst the mechanically actuated devices had an alarming or stressful effect. From this, it can be determined that the SMA-actuated devices are enjoyable, whilst the mechanically actuated devices are functional rather than enjoyable. When comparing the sensations to experiences in the real world, various similarities were mentioned. Objects are not necessarily enjoyable or not, making it hard to draw conclusions. However, mechanically actuated devices were often called artificial and weird, indicating an unenjoyable experience. Additionally, the mechanical consequences, such as vibration and noise, were mentioned a lot by participants. The repeated mentioning indicates that it diminished the experience of the sensation, and certainly did not contribute to the enjoyment.

The enjoyment of the sensation by the user is recognized in the semantic differential scale questions in the pleasantness scale. The results gathered from the user tests showed that the actuation method has a significant influence on the pleasantness experience or enjoyment of the user. They showed that SMA-actuated devices were experienced as more pleasant in general compared to the electromechanically actuated devices. The variation in speed or force did not influence this.
From the pleasantness scores and the feedback gathered during the introduction to the sensation, it can be concluded that the SMA-actuated devices are generally more enjoyable than the mechanically actuated devices.

Interpretation

During the introduction to the sensation, the participants were asked to describe similar sensations to the experienced sensation. The SMA-actuated sensations were often compared to a human touch; with the mechanically actuated sensations, this was rarely mentioned. Other comparisons, outside human touch, were similar for both sensations. The squeeze sensation was often compared to an elastic or blood pressure measuring band. The stroking sensation was often compared to a feather or a toothbrush.

During the semantic differential scale section, the humanlikeness was scored by the participants. The results from this question are in line with the results from the introduction to the sensation. The SMA actuated devices are experienced as more humanlike.
While the comparisons to real-world sensations provide insight into how participants related to the sensations, another aspect of interpretation lies in how they perceived the force and speed of the actuation itself. The results from the semantic differential scale section of the user test show that the mechanically actuated devices are perceived as providing higher force as well as higher speed compared to the SMA actuated devices. However, the SMA actuation was able to provide interpretable differences in force, whilst this was not the case for the mechanical actuation. In contrast, the SMA actuation did not provide noticeable differences in speed, whilst the mechanical actuation was able to.

Preferred scenarios

For scenarios where the enjoyment of the user is the priority, SMA actuation is most probably the suitable actuation method, whereas the mechanically actuated devices proved to be more functional. This functionality would be beneficial in scenarios where a warning needs to be given to the user.

The intended effect created by the two actuation methods is different. In a scenario where a comforting and pleasant touch is desired, SMA actuation should be selected. This could be applied in a scenario in which the user has a fear of crowded places and needs a grounding sensation in case of a panic attack. However, when the sensation needs to create a sense of urgency and to feel intense, mechanical actuation should be selected. In a medical scenario, this could be applied.

In the results gathered during the introduction to the sensation through open questions, the noise of the conventional mechanical actuation was mentioned often. In the baseline comparison this was already mentioned, however, during user testing it became apparent that this had a bigger impact on the effect on the participants than expected. The effect of the sensation of the mechanical actuation devices was generally shocking and alarming which was most likely also influenced by the noise of the actuation. In contrast to this alarming effect, the devices using SMA actuation had a comforting effect.

SMA actuation should be used in a scenario in which humanlikeness is needed. In both the introduction to the sensation and the semantic differential scale question regarding humanlikeness, SMA actuation was experienced as more humanlike. During the introduction to sensation, the SMA-actuated sensations were more often compared to a human touch, and the humanlikeness scores were significantly higher than the mechanical actuation. This could, for example, be very beneficial in the AR/VR haptics field.

The actuation method can also be selected based on performance metrics, instead of the experience of the sensation. As discussed before, SMA actuation can produce more noticeable differences in force compared to mechanical actuation. For example, a scenario in which first a gentle sensation needs to be provided as an alert, after which a more forceful sensation needs to be delivered for the second reminder. However, if only the forceful sensation is required, the mechanical actuation is more suitable.

When speed is the key metric in the sensation, mechanical actuation can provide high speed or a noticeable variation in speeds. Varying speeds can be required in a scenario where a high-speed movement is needed to grab the attention of the user in case of a panic attack, after which the movement will slow down in order to calm them down. However, a gradual movement created by SMA actuation is inherently experienced as more comforting. Therefore, the need for varying speed should be carefully evaluated based on the specific scenario. This would be less debatable in a scenario in which the fast movement is used to grab attention, and the slow movement is used to keep the focus of the user on a certain task.

Limitations

During the process of gathering the previously discussed results, there are some factors that influenced the outcome, possibly also influencing the final conclusions regarding the comparison between actuation methods. These influences regard the design of the devices and differences between participants.

Device design

The devices were designed to provide similar sensations to the participants, however, this was not fully achieved.

The squeeze sensations created differed in the speed of the actuation. The sensation created by the SMA-actuated device was a gradually increasing squeeze, whilst the mechanical device was quicker, instant squeezing. The participants mentioned this often as one of the differences between the sensations. By adjusting the Arduino code, a more gradual squeeze could be created by the mechanical device, making the sensations more similar.

Additionally, the material that was in contact with the skin of the participants of the two squeeze devices was not the same. The SMA-actuated squeeze device made use of materials that could withstand and block the heat of the wire, whilst the mechanical squeeze device made use of a leather strap due to research showing this is enjoyed by users. By incorporating the leather into the SMA squeeze device as the final layer in contact with the participant, this difference can be overcome, or by adding the sporting tape material to the strap of the mechanically actuated squeeze device.

The biggest difference between the stroking devices was the location of the stroke. The SMA-actuated stroke was felt closer to the wrist, whilst the mechanically actuated stroke was located more towards the elbow. Some participants indicated that the location of the stroking sensation influenced the pleasantness of the experience.

Finally, for the SMA actuated stroking device, a decline in performance was observed. Whilst the first participants experienced a stroke of around four centimetres, the last participants experienced a stroke more towards two centimetres. This most likely influenced the experience of, amongst others, pleasantness and intensity for the participants.

Participant variability

To study the influence of the actuation method, the aim was to have all participants experience the same sensation. However, since all bodies are unique, this was not the case.

Due to differences in wrist and arm sizes, the contact of the end effector or both devices was different between participants as well. For some participants, the end effector was pressed against the arm, and for others the end effector had little to no contact with the arm at all. As a result of this, some participants experienced a rubbing sensation, and some experienced a sensation similar to a feather along the arm. To mitigate the problem of the end effect having no contact with the arm, an additional layer of leather was used. However, because of this, the experience between participants was not exactly the same.

The SMA actuated squeeze device sizes were based on a female wrist size. However, when fitting the device to a male wrist, the SMA wire was too short to fit around the wrist completely. The gap was bridged using Velcro, however, this does create a different sensation compared to the SMA actuator reaching fully around the wrist.

Recommendations

The project approach used was able to provide interesting insights, however, the tools used to gather the data can be refined further. The conclusions from the design process perspective are mainly based on the radar chart. The conclusions from the user experience perspective are based on the user test. In the following section, the possible refinement of these tools for future research is discussed. Additionally, new directions for future research are presented.

Radar chart refinement

There are several points of improvement for the radar chart metrics, therefore, it would be recommended to improve the radar chart used. From the design experience, it becomes apparent that there was more information gathered on working with either actuation method, which was not captured in the chart. Primarily, the range of the technical axes should be reconsidered. For this project, the axes were determined by literature gathered during a systematic review. When using the radar chart to evaluate the designed devices, it became apparent that the subtle differences could not be captured in the big ranges determined for the technical metrics. For future usage of the radar chart, the range of axes should be adjusted to capture the desired order of magnitude suitable for the devices.

In the current radar chart, the power-to-weight axis is directly determined based on the force and weight metrics, which are also displayed in the chart. Whilst the power-to-weight is interesting, the information is already provided. For future usages of the chart, the force, weight and power-to-weight axes should be reconsidered based on the application. When a quick overview of the power-to-weight ratio is desired, it could be considered to remove the weight axis. However, if a very lightweight device is desired, the power-to-weight and/or the force axis could be omitted. In this project, the different sensations show how the information from the different axes provide greater insight in various situations. When analysing the stroking devices, the weight axis was more meaningful, since force was not a goal for this sensation. However, for the squeezing devices, the power-to-weight metrics provided interesting insights, as this quickly displayed multiple specifications of the device.

The current set-up of the user experience metrics did not appear to cover the full experience. Mainly, the ratings of the three user experience metrics from the device experience section did not provide the expected insights. The scores of the three metrics are not highly different, and during the user tests, the justification of the scores by the participants appeared to be based on similar aspects of the devices. Additionally, the final calculation of the scores, used to reduce the several questions answered to three metrics, was not thoroughly developed. A solution could be to present the participants with one question for each metric only, and to highlight clearly the different aspects that influence each metric. Another option could be to implement meaningful weights to all sub-questions, based on literature or on the participants' opinions. Finally, the question regarding the harm done by the device was not very meaningful, as any painful parts were redesigned during the design phase.

In the current chart is the movement translation used in the devices not captured, whilst it did influence the controllability of the devices. To capture this, the controllability metric should be redefined. By focusing on the definition of the metric on the control over the final movement, the meaning and impact of the metric is more clearly interpretable. Additionally, the aspects currently mentioned in the metric description can be defined as well. For example, control over the time taken to complete the movement, control over the final force, or control over a gradual increase in speed. The reliability of the devices is also not reflected in the current radar chart. During the user tests, the stroking devices did not always work well, with the mechanically actuated device sometimes stalling and the SMA actuated device not being in contact this the participant's arm. Whilst these issues can be mitigated by improving the design of the devices, working with the actuation method does become more challenging when more restrictive aspects need to be taken into account.

User test refinement

The user test conducted during this project provides a lot of interesting insight regarding the activation methods. By refining the user test for any future research, even more conclusions can be drawn.

Firstly, several user-specific characteristics influence the experience of the sensation, which were not taken into account during the user test or analysis of the results. For example, the sensation felt different on the dominant hand compared to the non-dominant hand. This became clear from the comments given by the participant, and because participants gave different scores to the same sensation on the other arm. Some participants also noted that the squeeze sensation felt more familiar on their left arm, because they usually wear a watch. Since during the user test the participants experienced the sensation on both wrists, any potential influence of these characteristics was averaged in the analysis. However, for any future research, it could be interesting to explore the interaction between these characteristics and the actuation methods. By measuring the size of the wrist and tracking whether a participant wears a watch, it can be explored if these have an influence on the sensation and if this differs per actuation method.

Additionally, during the testing, the age variation of the participants in this project was limited, and the male-female ratio was skewed. This type of data was also not logged, so the data gathered per participant was not linked to this kind of information. Meaning that, for this project, the influence of age or gender on the experience of the sensations could not be looked into. Therefore, this could also be taken into account in any future user testing.

During the semantic differential scale section of the user test, quantitative data were gathered.

However, there were also several qualitative comments given by participants. For future testing, it could be insightful to encourage all participants to justify their answers to discover the exact meaning. For example, the intensity of a sensation influences the enjoyment of the sensation for the user (Vallgårda et al., n.d.). However, this can appear in both a negative sense as well as a positive sense. During the user test, this was also reflected in several comments made by the participants, mentioning that the sensation was intense in a bad way or a good way. Therefore, for future research, it would be interesting to track whether the intensity is positively or negatively experienced and see if this is connected to the actuation method.

It became clear that, when rating the pleasantness of a sensation, some participants preferred a light squeeze and others a firmer squeeze. By including a section to establish a baseline preference for each participant, for example by squeezing the arm of the participant by hand, more insight into the exact influence of the actuation method can be discovered. When including a section where actual human touch is experienced, the question regarding humanlikeness is most likely also easier to answer for the participants. Similarly, the section of the user test in which the device impression is given by the participant could also use an example scenario. If the participants acted out or were vividly described a scenario in which the device could be used, they could imagine the practical application of the device. Currently, the questions regarding the wearability of the devices in the context of daily life are harder to answer if the device serves no clear purpose to them. When the device provides great advantages, users might be more willing to wear more obstructing devices (Puri et al., 2017). Similarly, the question regarding the feeling of the sensation needs to be developed better. The current set-up takes no context into account, whilst this is highly influential on the feeling of a sensation. Experiencing a scenario and feeling the sensation in this context could improve the feedback given on the devices. This way, more complex influences of the actuation method could be discovered, as well as identify specific application scenarios for each actuation method.

Future research directions

As previously discussed, there are many improvement points in the tools used during this project. In addition to processing these for future research, there are several more directions to explore and expand on the results gathered during this project.

Firstly, the conclusions drawn and specifically the decision flowchart presented in the conclusion (Figure 78), should be validated. Future research should verify its usefulness and effectiveness in practical design cases. This could include collaborating with designers from different fields to see how they use the flowchart and whether it improves their decision-making process or final design outcomes.

As mentioned before, there are many design opportunities with both actuation methods. Therefore, an initial next step for this research could be to redesign the haptic devices and explore if the results and conclusions would be similar. Shortcomings of the devices identified in the section above could be the focus of a new iteration, discovering if this influences the results and overall conclusions regarding the actuation methods. By conducting this research, the results found in this research will either be more strongly substantiated or new correlations between metrics will be discovered that this project has not uncovered yet.

Future research should also be done looking into long-term usage of the haptic wearables. The user experience metrics are most likely influenced when wearing a wearable for long periods. Additionally, can be more substantiated research be done into the durability of the devices. Since in this project the devices were used only around a hundred times, the device have not been properly been tested on their life cycles.

Expanding the project using new sensations would be interesting. During this project, two contrasting sensations are used to explore the design space. So, when including another or more different sensations, more correlations between metrics and influences of the actuation methods could be identified. A pinching sensation could be a movement placed in between the squeeze and stroking sensations since this is a sensation that includes both medium displacement as well as medium force. This way the decision flowchart can be expanded by adding more decision nodes, for example, a third option in the key metric decision node such as response time.

Future research could be done into more specific application within the affective haptics field. For example, the influence of the actuation method could be different when designing wearables for anxiety disorders compared to wearables designed to calm kids with ADHD. By researching more specific applications, the decision flowchart could also be expanded into one that splits at a higher level based on these results. Additionally, the research could expand into new haptic fields. Currently, the project focuses on affective haptic, however, expanding similar research into the VR/AR haptics field would be interesting. The high scores in humanlikeness for the SMA actuation could be a great advantage. However, the slow reaction time could present a limitation, making the actuation method unsuitable. Additionally, the VR/AR haptics field is growing, and many new developments are happening for which it would be useful to get an overview of the suitable actuation method in several scenarios.

The current comparison is limited to two actuation methods: shape memory alloy and conventional electormechanical actuation. However, there are many more actuation methods currently available for which it would be helpful to create an overview. A new actuation method could be introduced to the current project, by designing a squeezing device and a stroking device, and comparing how these perform to the devices designed. Pneumatic systems were excluded from this project, even though they appear well suited to provide the squeezing and stroking sensations.

Finally, an interesting aspect of the actuation methods that has not been taken into account during this project is sustainability. By doing a life cycle assessment (LCA) of the haptic wearables, the environmental impact can be determined and could provide advice to designers with sustainability requirements. An LCA will take the impact of the raw materials of the device into account, the use of the wearable, and the disposal or recycling of the materials afterwards.

Conclusion

This project was completed with the aim to answer the following question: How do SMA and electromechanical actuation compare in affective haptic wearables? This comparison was made from a design process perspective as well as a user experience perspective. These perspectives compared activation methods at different levels, from which insights were gathered on how the activation methods can be distinguished and selected. The following provides a short overview of the main conclusions.

The study showed the strengths of SMA actuation lie in creating pleasant and humanlike sensations and providing the ability to create comfort for the user. Mechanical actuation is perceived as intense and creates a sense of urgency in the user. However, this actuation method does enable precise control and high-frequency repetition. This is reflected in the variation in speed, which is clearly perceived by the user when mechanical actuation is used. Yet, variations in force are noticed by the user when SMA-actuation is used.

These insights were used to compile a decision flowchart, which is presented in the following chapter (Figure 78). The flowchart can provide designers with guidance on which actuation method to use for their application. Additionally, three examples are used to demonstrate how the flowchart can be applied.

Decision flowchart

In Figure 78, the created decision flowchart is presented. The flowchart is used by starting at the 'start' square and following the arrows. Decision nodes are depicted using a diamond shape. Next to the arrows originating from the decision node, the selection options are displayed. By following the arrow with the selection option suitable for the project, the next decision node or advised actuation method is found. The SMA actuation method is displayed in a green circle, and the electromechanical actuation method in a blue circle.

Justification

The flowchart is structured this way based on several insights gained during this project. The top of the flowchart has two nodes that are based on technical and performance limitations of the actuation methods. Then, the key metrics that were explored in the designed devices and during the user tests split the flowchart into two directions. The final decision nodes mostly regard the user experience of the sensation. This way, it is ensured that the requirements are met first, after which the wishes regarding a sensation are addressed.
The pattern of the intended sensation is addressed in the first decision node. SMA actuation is unable to provide high-frequency repetition for a sensation due to the cooling time, therefore, if this is needed, only mechanical actuation could be suitable. Similarly, mechanical actuation is not suitable if several sensations close together are desired, leading to SMA actuation as the suggested choice. As these are technical limitations of the actuation methods, this decision node is placed at the beginning of the decision flowchart.

The following node regards the sensation movement. This node is placed at the beginning of the flowchart for similar reasons as the sensation pattern. The mechanical actuation is unable to match the high flexibility of the SMA actuation. Meaning that, if a sensation along the curves of the body is needed, SMA actuation is much more suitable. In contrast, if a big movement is desired, SMA actuation is unable to perform as good as mechanical actuation.

The next node that is met regards the control over the final movement. This node is placed higher in the decision flowchart because the SMA actuation cannot be precisely controlled. Therefore, if this is required, classic mechanical actuation should be used.

From the results of the user test, it became clear that the force or speed of the sensation influences the perceived friendliness of the mechanically actuated devices significantly. Therefore, when only mechanical actuation is suitable in the situation of a lengthy movement, a decision node regarding friendliness is added. Since only mechanical actuation is suitable for big movements, this decision node points to two end points that both indicate mechanical actuation. However, the endpoint resulting from selecting that friendliness is of some importance, indicates that the mechanical actuation should be applied with low force and speed.

During this project, the force and the speed metrics were looked into. Therefore, at the decision node on key metrics, these are two of the options. If neither of these is applicable in the desired sensation, a third arrow indicates other metrics. Since the information gathered during the project was focused on the force and speed metrics, only general advice can be given when following this arrow. This advice is based on results that appeared in both the squeezing and stroking sensations and across the varying force or speed. The following decision node regards humanlikeness, as SMA actuation was experienced as more humanlike in the user test in all situations. Next, the intended effect of the sensation is addressed. The user test also showed that the mechanical actuation created a sense of urgency, whilst the SMA actuation provided a sense of security.

When selecting force as the key metric, the first decision node regards the experienced force by the user. The user tests showed that the mechanical actuation was generally perceived as high force, whilst differences in force were better distinguished by participants with the SMA actuated sensation. Therefore, the option of varying force is included besides the options high-force and low-force. If one device should be capable of conveying sensations at different forces, the SMA actuation is more suitable. The option indicating high-force points to a decision node regarding the humanlikeness. Since both SMA actuation and mechanical actuation are capable of providing a high force sensation, this decision node can determine which is more suitable for use, since SMA actuation is perceived as more humanlike.

When the key metric is speed, the next decision node regards the experienced speed by the user. The SMA-actuated sensation was generally perceived as slow, so if a high speed or a varying speed is desired, mechanical actuation is indicated as the suitable actuation method. When following the option indicating low speed, a decision node regarding the sensation experience is next. Mechanical actuation will provide an intense sensation, whilst SMA actuation will provide a pleasant sensation.

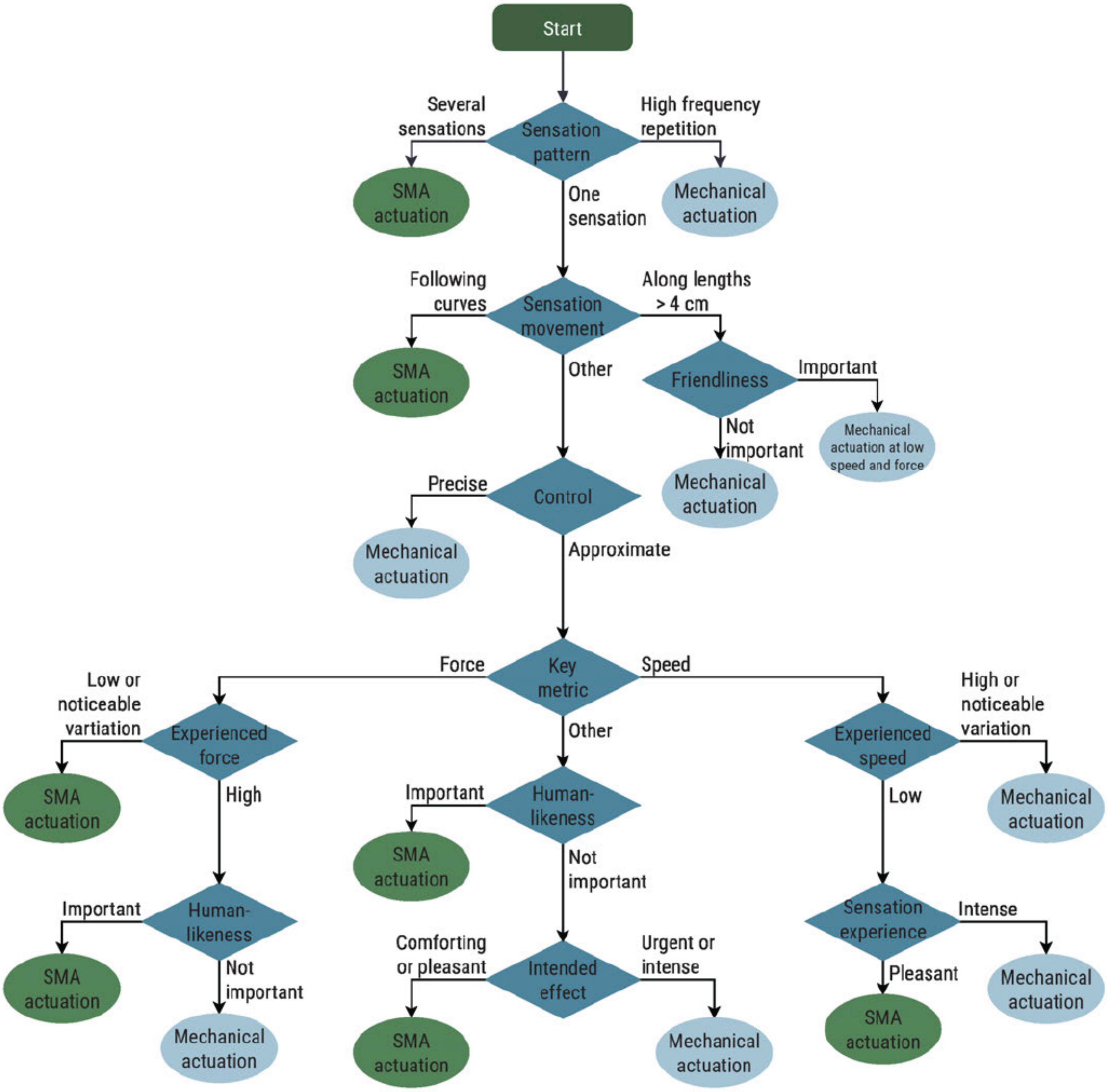


Figure 78 – Decision flowchart for selecting the suitable actuation method based on the application of the device

Application examples

To demonstrate how the decision flowchart can be used, several examples were compiled. In this section, these examples are presented.

The first example for application will be one where the aim is to create a pressing sensation on the upper back, reminding the user to sit straight. When arriving at node one, regarding the sensation pattern, the option indication ‘one sensation’ will be selected. Then, for the next decision node regarding the movement, neither along curves nor along lengths applies to this sensation, therefore, the option ‘other’ is followed. The control over the sensation does not have to be precise, thus, the option indication ‘approximate’ is followed. The key metric for this sensation will be force, thus, the arrow pointing left is followed. To remind the user to sit straight, the device should be available to exert higher force. However, if first a gentle reminder is desired, before a more forceful reminder is given, varying force would be necessary. As this flowchart is used as guidance, both options will be explored. First, the noticeable variation option is followed, which leads to SMA actuation. When following the high-force option, another decision node is presented regarding the humanlikeness. A reminder to sit straight does not have to be humanlike, which leads to the electromechanical actuation being suggested. From this example is becomes clear that the flowchart can be used as guidance and not as a definitive determination on which actuation method to use.

The second example sensation will be to create a calming breathing pattern. One way to achieve this could be with a swiping motion along the chest, another way could be to use a contracting pressure on the abdomen. For both options, the flowchart will be applied. For the swiping motion, one sensation is needed, following the arrow down from the sensation pattern decision node. A lengthy movement is needed, therefore, the arrow pointing right is followed. The breathing pattern is used to calm the user down; therefore, a friendly feeling is desired. A mechanical actuation using a low speed is recommended. For the breathing pattern using contracting pressure, instead of a lengthy movement, the device should follow the curve of the abdomen of the user. Following this arrow leads to the recommendation of SMA actuation. This shows that the way a sensation is created is important when selecting an actuation method, and merely aiming to recreate a breathing pattern is not enough.

The final example will concern a slow circular movement on the shoulder to provide comfort. This sensation is repeated, but not with high frequency. When following the high-frequency option, mechanical actuation is suggested. For now, the downward arrow, indicating one sensation, is followed. The movement is neither long nor along a curve, thus, the downward arrow is followed again. Since the control over the sensation can be approximate, the key metric decision node is met. A slow movement is desired; therefore, the key metric speed is selected. The speed perceived by the user should be low, following the downward arrow. As the aim is to provide comfort, the experience of the sensation should not be intense but rather pleasant. This indicates SMA actuation would be suitable for this sensation. However, as mentioned before, when the rate of repetition becomes a challenge, the switch to mechanical actuation should be considered.

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Appendix

Appendix A - Original project brief

DESIGN FOR our future

TUDelft

Personal Project Brief – IDE Master Graduation Project

Name student Tanja Overbeek

Student number 4,853,953

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title A Comparison between Haptic Feedback Systems using Shape Memory Alloys and Classical Skin Stretch Mechanics

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Haptic technology, meaning technology to addres the sense of touch, is nowadays widely used especially in many digital products, such as smart devices and public interfaces. The most often used form of haptic feedback is vibrotactile feedback, such as the buzzing of your smartphone device. However haptic feed also presents in other forms such as thermal feedback, texture feedback and force feedback. Currently there are plenty of methods using conventional mechanics to provide haptic feedback in many different forms, in figure 1 several examples of skin stretch devices are given.
Relatively new to the field of haptics is the use of shap memory alloys, such as Nitinol wires to produce haptic sensations. SMAs have an organic way of changing shape, therefore it is believed that the haptic feedback provided would feel more natural and pleasant (see figure 2). SMAs can be integrated in devices to act as actuators while being responsive, light and strong. The SMAs can change their shape in response to their environment, and thus be used to change the shape of structures in response to the user or their actions. The shape changing characteristics of the material itself can be designed in such a way that no external sensors or actuators are needed, and the actuation comes from the material only. This provides interesting opportunities for using the material in providing haptic feedback, however, currently there is still little know about the effectiveness of the SMAs in providing affective haptic feedback.
Especially how these two ways of providing haptic feedback, SMAs and classic skin stretch mechanics, relate to eachother is still undiscovered. Where do the opportunities of either of these actuation methods lie and when would one be more suitable to use over the other.

Aggravi, M., Pausé, F., Giordano, P. R., & Pacchierotti, C. (2018). Design and Evaluation of a Wearable Haptic Device for Skin Stretch, Pressure, and Vibrotactile Stimuli. *IEEE Robotics and Automation Letters, 3* 3(3), 2166-2173. IEEE Robotics and Automation letters. https://doi.org/10.1109/LRA.2018.2810887

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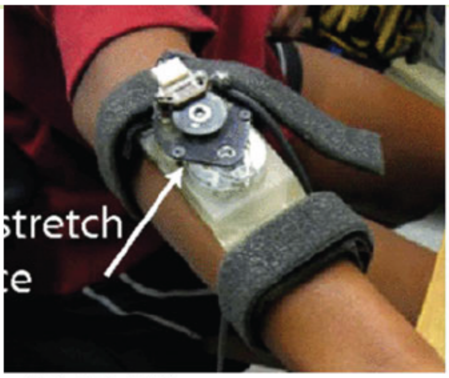
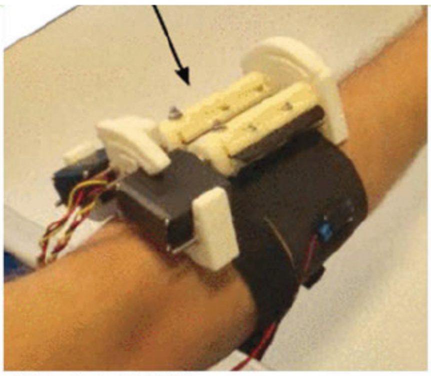
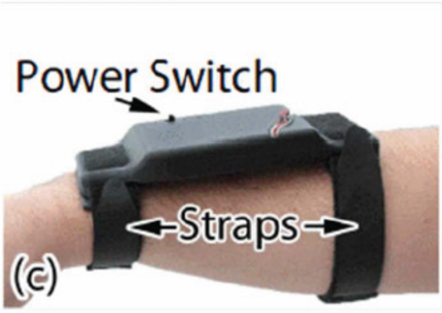
introduction (continued): space for images



(Bark et al., 2009)



(Aggravi et al., 2018)



(Caswell et al., 2012)

(Chinello et al., 2018)

image / figure 1 Conventional Skin Stretch Devices used to provide haptic feedback

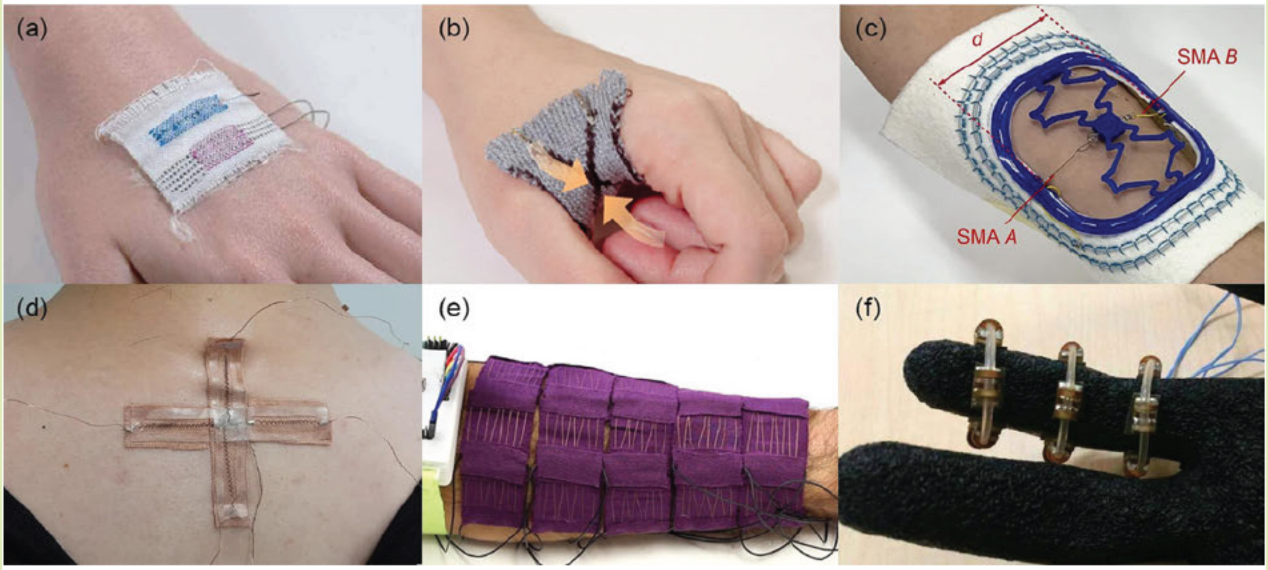


image / figure 2 Shape Memory Alloys used to provided different types of haptic feedback (Liu et al., 2023)

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

I wish to uncover how shape memory alloys (SMA) compare to conventional skin stretch mechanics when being used as actuators in haptic feedback wearables. I will look into the design process and the user experience during this project. By quantifying parameters relevant to both actuator methods using literature, the actuator can be assessed similarly. By going through several iterations of designing haptic wearables with both actuators, focussing on different parameters, I aim to capture a broad design experience and compare these to each other. Secondly, I want to explore the user experiences using the different wearables, looking for initial impressions of the participants. I wish to explore factors such as comfort and intuitiveness and how the participants experience the differences between wearables and actuators. By looking into both the design process and the user experience, I aim to be able to provide recommendations to future designers in regard to the suitable actuation method.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

I want to draw a comparison between two actuator methodes, shape memory alloys and conventional skin stretch mechanics, for wearable devices providing haptic feedback to map out the design process and the user experience.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

I want to start my project by learning about the possibilities with the SMA material and the currently available skin stretch mechanics. During this discovery phase, I want to learn to work with the actuators physically as well as learn the theoretical knowledge from literature. From literature, I want to extract quantifying parameters of the actuators that are relevant when comparing haptic wearables. I will identify the properties and parameters of SMA and the conventional skin stretch mechanics so that they can be assessed similarly. After exploring possibilities with the materials, I will move to the design phase. Based on these parameters I will explore the design options of both actuator methods. By going through several iterations, and prioritizing different parameters over the iterations, I wish to uncover the design experience of the actuator methods. Hereafter, I want to conduct user tests to assess how different parameters affect the user's experience as well. During this whole project, insights will be gathered to be able to formulate proper design recommendations.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	12 nov 2024
Mid-term evaluation	20 jan 2025
Green light meeting	24 mrt 2025
Graduation ceremony	21 apr 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

I wish to start this project because I find Shape Memorie Alloys very interesting. I wish to explore many different ways of using the SMA's and generally learn how to apply them in future projects as well.
Additionally I enjoy tinkering with conventional mechanics. I have limited experience with electronics such as Arduino and would like to expand and develop this. I believe that there is a giant market of mechanical components which I would like to familiarize myself with and develop my abilities to selection suitable or the best components for the application.
I also wish to develop my project management skills. I tend to struggle with staying on track, especially with solo projects. This individual project lasting 20 weeks will definitely test these capabilities.
During this project I wish to prove my prototyping skills and my resourcefulness when running into problems. I am looking forward to the prototyping aspect of this project most, I enjoy working physically and am excited to combine this with a material new to me. During the prototyping phase I also believe my creativity and resourcefulness will come into play, to come up with new solutions and troubleshoot when necessary.

Appendix B - systematic review

The systematic review was done according to the PRISMA guideline (Page et al., 2021). Web of Science was used to gather the papers. The following selection criteria were used:

- The paper concerns a haptic wearable
- Cutaneous feedback
    - Shear and normal forces
- A complete prototype was made
- Device details are discussed
- Any application

The following papers were used to determine evaluation metrics for skin stretch devices:

Aggravi et al., 2018; Bark et al., 2009; Casini et al., 2015; Caswell et al., 2012; Chase et al., 2020; Chinello et al., 2018; Colella et al., 2019; Dunkelberger et al., 2018; Gil et al., 2022; Horie et al., 2023; Husman et al., 2016; Ion et al., 2015; Kayhan & Samur, 2022; Kent, 2023; Kim et al., 2024; Kuang et al., 2022, 2024; Lee et al., 2022; Leonardis et al., 2017; Meli et al., 2018; Mo et al., 2019; Pan et al., 2017; Schorr & Okamura, 2017; Zhuwawu et al., 2023

The following papers were used to determine the evaluation metrics for shape memory alloy devices:

Aiemsetthee & Sawada, 2020; Dulger et al., 2023; Foo et al., 2020; Foo, Lee, Compton, et al., 2019; Foo, Lee, Ozbek, et al., 2019; Gupta et al., 2017; Hamdan et al., 2019; Haynes et al., 2019; Hwang et al., 2017; Lim et al., 2019; Muthukumarana et al., 2019, 2020; Nakamura & Jones, 2003; Simons et al., 2020; Solazzi et al., 2011; Ueda et al., 2020

Appendix C – Arduino code squeeze device

```
/* Sweep
 by BARRAGAN <http://barraganstudio.com>
 This example code is in the public domain.

 modified 8 Nov 2013
 by Scott Fitzgerald
  https://www.arduino.
cc/en/Tutorial/LibraryExamples/Sweep
*/

#include <Servo.h>

const int sensorPin = A0; //pin A0 to read
analog input

//Variables:
float value_high; //save analog value
const float translate = 0.0307692308;
float N;
float value_new;
int i = 0;

Servo myservo;  // create servo object to
control a servo
// twelve servo objects can be created on mos
boards
Servo myservo2;

const int buttonPin = 4;     // the number of
the pushbutton pin
const int servo = 3;
```

```
int pos2 = 1;     // variable to store the
servo position
int pos = 180;
int steps = 125;
int buttonState = 0;

void setup() {
   Serial.begin(9600);
  myservo.attach(3);   // attaches the servo o
pin 9 to the servo object
   myservo2.attach(7);
  // initialize the pushbutton pin as an inpu
   pinMode(buttonPin, INPUT);
   myservo.write(pos);
   myservo2.write(pos2);
}

void loop() {
   buttonState = digitalRead(buttonPin);

/*   if ((buttonState == HIGH) && (pos == 40))
     for (pos = 40; pos <= 140; pos += 1) { //
goes from 0 degrees to 180 degrees
       // in steps of 1 degree
       myservo.write(pos);                // tel
servo to go to position in variable 'pos'
       delay(5);                          // wait
15 ms for the servo to reach the position
       }
  }*/
```

```
 if ((pos2 < 2) && (buttonState == HIGH)) {
   i = 0;
   value_high = 0;
   pos2 = steps;
   pos = 180 - steps;
   myservo.write(pos);
   myservo2.write(pos2);
   delay(1000);
   while (i < 10) {
      value_new = analogRead(sensorPin);
      if (value_new > value_high) {
        N = value_new * translate;
        Serial.println(N);
        value_high = value_new;
        delay(100);
        }
      i += 1;
      Serial.println(i);
      }
   pos2 = 1;
   pos = 180;
   myservo.write(pos);
   myservo2.write(pos2);
   delay(1000);
 }

/* buttonState = digitalRead(buttonPin);

 if ((pos > 30) && (buttonState == HIGH)) {

 }*/
```

```
  buttonState = digitalRead(buttonPin);
}
```

Appendix D – Arduino code stroking device

```
int pwm1 = 9;
int pwm2 = 10;
int ctr_a = 9;
int ctr_b = 8;
int ctr_c = 11;
int ctr_d = 10;
int sd = 6;
int i = 0;
int t = 2000; //speed of the rotation
int j = 0;
const int buttonPin = 4;
int buttonState = 0;
int rl = 0;
int dis = 60;

void setup()
{
   Serial.begin(9600);
   pinMode(ctr_a, OUTPUT);
   pinMode(ctr_b, OUTPUT);
   pinMode(ctr_c, OUTPUT);
   pinMode(ctr_d, OUTPUT);
   pinMode(buttonPin, INPUT);
   delay(1);
}

void right() {
  for (i = 0; i < dis; i++)  {
     digitalWrite(ctr_a, LOW); //A
     digitalWrite(ctr_b, HIGH);
     digitalWrite(ctr_c, HIGH);
     digitalWrite(ctr_d, HIGH);
     delayMicroseconds(t);
     digitalWrite(ctr_a, LOW);
     digitalWrite(ctr_b, HIGH);
     digitalWrite(ctr_c, HIGH); //DA
     digitalWrite(ctr_d, LOW);
     delayMicroseconds(t);
```

```
    digitalWrite(ctr_a, HIGH);
    digitalWrite(ctr_b, HIGH);
    digitalWrite(ctr_c, HIGH); //D
    digitalWrite(ctr_d, LOW);
    delayMicroseconds(t);
    digitalWrite(ctr_a, HIGH);
    digitalWrite(ctr_b, HIGH);
    digitalWrite(ctr_c, LOW); //CD
    digitalWrite(ctr_d, LOW);
    delayMicroseconds(t);
    digitalWrite(ctr_a, HIGH);
    digitalWrite(ctr_b, HIGH);
    digitalWrite(ctr_c, LOW); //C
    digitalWrite(ctr_d, HIGH);
    delayMicroseconds(t);
    digitalWrite(ctr_a, HIGH);
    digitalWrite(ctr_b, LOW);
    digitalWrite(ctr_c, LOW); //BC
    digitalWrite(ctr_d, HIGH);
    delayMicroseconds(t);
    digitalWrite(ctr_a, HIGH);
    digitalWrite(ctr_b, LOW); //B
    digitalWrite(ctr_c, HIGH);
    digitalWrite(ctr_d, HIGH);
    delayMicroseconds(t);
    digitalWrite(ctr_a, LOW);
    digitalWrite(ctr_b, LOW); //AB
    digitalWrite(ctr_c, HIGH);
    digitalWrite(ctr_d, HIGH);
    delayMicroseconds(t);
    Serial.println(i);
   }
   rl = 0;
}

void left() {
  for (i = 0; i < dis; i++)  {
       digitalWrite(ctr_a, LOW); //A
```

```
digitalWrite(ctr_b, HIGH);
digitalWrite(ctr_c, HIGH);
digitalWrite(ctr_d, HIGH);
delayMicroseconds(t);
digitalWrite(ctr_a, LOW);
digitalWrite(ctr_b, LOW); //AB
digitalWrite(ctr_c, HIGH);
digitalWrite(ctr_d, HIGH);
delayMicroseconds(t);
digitalWrite(ctr_a, HIGH);
digitalWrite(ctr_b, LOW); //B
digitalWrite(ctr_c, HIGH);
digitalWrite(ctr_d, HIGH);
delayMicroseconds(t);
digitalWrite(ctr_a, HIGH);
digitalWrite(ctr_b, LOW);
digitalWrite(ctr_c, LOW); //BC
digitalWrite(ctr_d, HIGH);
delayMicroseconds(t);
digitalWrite(ctr_a, HIGH);
digitalWrite(ctr_b, HIGH);
digitalWrite(ctr_c, LOW); //C
digitalWrite(ctr_d, HIGH);
delayMicroseconds(t);
digitalWrite(ctr_a, HIGH);
digitalWrite(ctr_b, HIGH);
digitalWrite(ctr_c, LOW); //CD
digitalWrite(ctr_d, LOW);
delayMicroseconds(t);
digitalWrite(ctr_a, HIGH);
digitalWrite(ctr_b, HIGH);
digitalWrite(ctr_c, HIGH); //D
digitalWrite(ctr_d, LOW);
delayMicroseconds(t);
digitalWrite(ctr_a, LOW);
digitalWrite(ctr_b, HIGH);
digitalWrite(ctr_c, HIGH); //DA
digitalWrite(ctr_d, LOW);
```

```
        delayMicroseconds(t);
        Serial.println(i);
    }
    rl = 1;
}


void loop () {
  buttonState = digitalRead(buttonPin);
  if ((buttonState == HIGH)&& (rl == 1)) {
    right();
    }
  buttonState = digitalRead(buttonPin);
  if ((buttonState == HIGH) && (rl == 0)) {
    left();
    }
  buttonState = digitalRead(buttonPin);
}
```

Appendix E – User test plan

User test protocol

These user tests will be conducted to discover the experience of the user regarding the sensation. Through open questions and semantic scale questions information will be gathered.

Set up

Supplies

- Cover for over the arms
- Power supply
- Laptop with Arduino code
- SMA Squeeze device
- Mechanic Squeeze device
- SMA Stroking device
- Mechanical Stroking device
- Printed question
    - Introduction
    - Semantic scales
    - Design process questions

Participants

Aim for 20 – 25 participants. Convenience sampling will be used.

Set-up

The participant will be sitting down, with his/her arms behind a barrier so their wrists are not visible to them. A device will be attached to both wrists of the participant. They will feel a haptic sensations alternating between wrists.

The user test consists of two sections, one addressing the squeezing sensation and one addressing the stroking sensation. It will be randomized with sensation is experienced first between participants. A section is opened with an introduction to the sensation. Here the participant will experience the sensation where the force or speed is averaged. After each of the actuation methods they will then give their first impressions and opinions regarding the sensations. Then they will also be asked to compare the sensations and highlight the differences if they feel any.

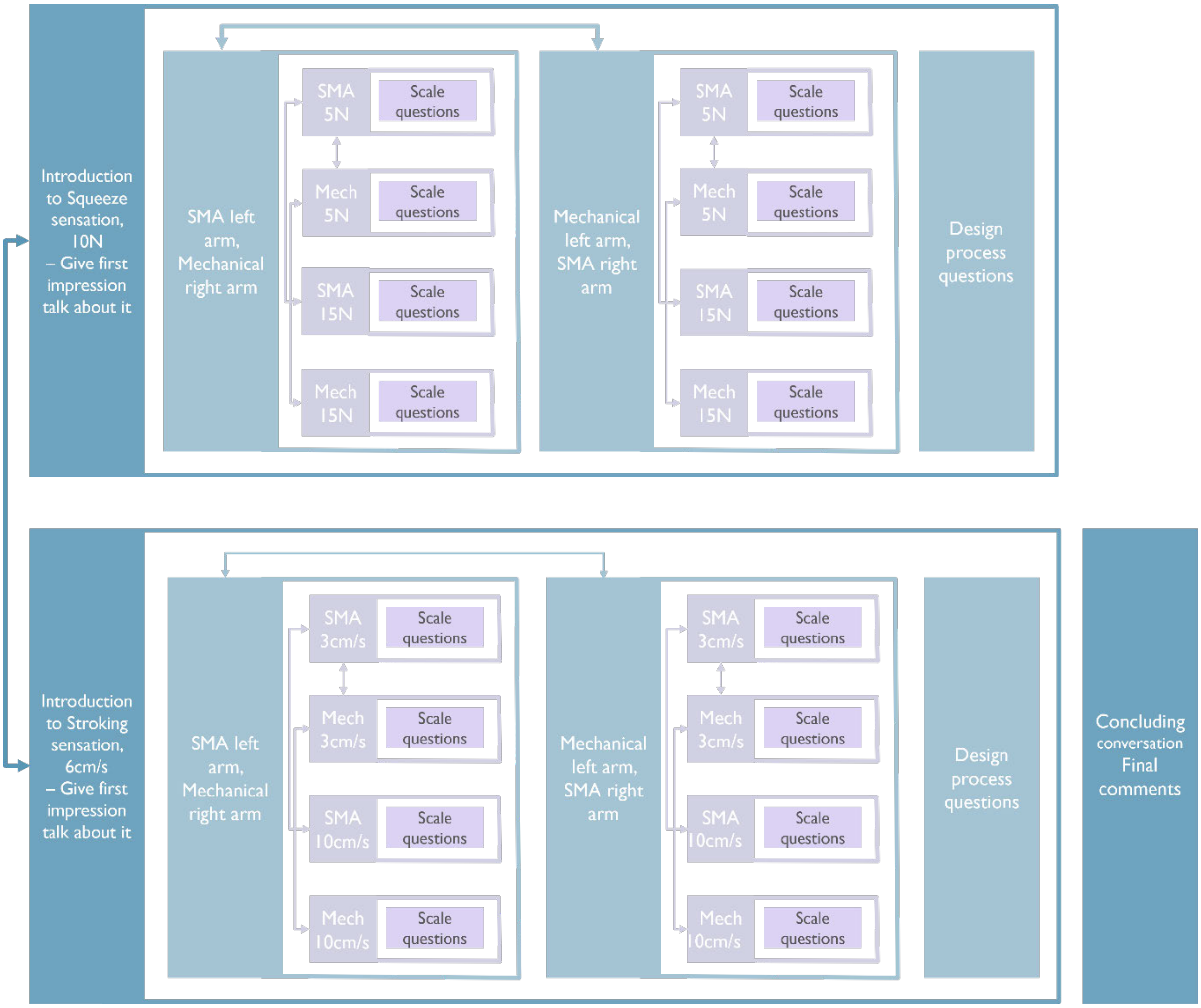
For each section, there are two subsections. Between these subsection the devices will be switched to the other arm, this way both actuation methods are felt on each arm. Within the subsections four sensations will be experienced, two for each actuation methods with a varying force or speed. The order of the variations will also be randomized. After experiencing a sensation the participants will be asked to answer several questions given as semantic scales.

After the two subsections are completed, the participant is allowed to see their wrists and move around a little. They will then be asked several questions about the experience of wearing the devices (design process research questions). These questions have to be answered twice, once for each actuation method on either arm.

The second section has the same structure as described above. To conclude the user test the participant will be asked for any final comments or remarks regarding the sensations.

Structure (Image on next page)

- Section 1 (Squeeze or Stoking)
    - Introduction to the sensation
        - Per actuation method
            - First impression
            - What does it feel like
            - How does it make you feel
        - Comparing them
            - Similar or different
            - If different, how
    - Block 1
        - Four sensations
            - Randomize the starting actuation method
            - Randomize the varying force/speed
        - Questions between each
            - Pleasantness
            - Intensity
            - Human-likeness
            - Force or speed
            - Mean vs friendly
    - Block 2
        - Four sensations in random order
            - Randomize the starting actuation method
            - Randomize the varying force/speed
        - Questions between each
            - Same questions as above
    - Design process questions
        - Wearability
        - Ergonomics
        - Impairment
- Section 2 (Squeeze or Stoking)
    - Repeat steps as described above
- Final discussion
    - Discuss experience of the participant
    - Final questions and comments of participants



Process of the user test visualizes, arrows indicate that the order can be changed

Introduction to the sensation

Please tell me you first impression

What does this sensation feel like to you?

How does this sensation make you feel?

Do these sensations feel similar or different?

→ Please describe the difference that you felt:

Questions discussed during the introduction to the sensation

The top section is repeated twice, once for each actuation method. Then the bottom section is discussed.

The interviewer will discuss and note down answers.

Semantic scales

1. Please rate the pleasantness of the sensation:

Unpleasant — Pleasant

2. Please rate the intensity of the sensation:

Weak — Strong

3. Please rate the human-likeness of the sensation:

Not human-like — Very human-like

4a. Please rate the force of the sensation:

Weak — Strong

4b. Please rate the speed of the sensation:

Slow — Fast

5. Please rate the feeling of the sensation:

Mean — Friendly

These question are asked after each sensation, which means they are repeated 16 times. Questions will be printed to aid the participants in answering. Interviewer will note the answers digitally.
Question four a or b will be asked depending on which sensation is tested. When testing the squeezing sensation, the question regarding force is answered by the participant. For the stroking sensation the question regarding speed is asked.

Design process

Wearability	The wearability of a device in a social context, in daily life	Not wearable	Very wearable
Disruption	Distraction by the sensation from your surroundings	Very disruptive	Not disruptive
Emotion	Concerns about appearance and relaxation	Very concerning	Not concerning
Anxiety	Worry about the device, safety, and reliability	Very worried	Not worried
Impairment	Does the device obstruct in any way	Very obstructive	Not obstructive
Movement	The device physically affects movement	Very affected	Not affected
Perceived weight	How does the weight feel on your body	Heavy	Light
Perceived change	Feeling physically different	Very different	Unchanged
Ergonomics	Does the device fit your body	Does not fit	Fits well
Attachment	Physical feel of the device on the body, attachment	Uncomfortable	Comfortable
Harm	Physical effect, damage to the body	Painful	Not painful

Question to be answered at the end of each section. Participant is now allowed to see the devices and move around. Questions will be printed, answers will be recorded digitally.

Device fittings

Behind a curtain the SMA and Mechanical version of the sensation are attached to both wrists. The participant will first experience all the sensations twice before they are allowed to see the devices.

Squeeze

5N SMA • Attach the device using the Velcro • Set the power supply to 3V • When the participant is ready, turn on for 2s • Turn of • Ask the participant to answer the questions	10N SMA • Attach the device using the Velcro • Set the power supply to 6.5V • When the participant is ready, turn it on for 3s • Turn of • Ask the participant to answer the questions	15N SMA • Attach the device using the Velcro • Set the power supply to 8V • When the participant is ready, turn it on for 4s • Turn of • Ask the participant to answer the questions
5N Mech • Attach the servo motor to the Arduino • Attach the body of the device to the participant using the Velcro • Attach the squeezing belt at neutral tightness • Screw on cover • Set var = 110; • Press button • Ask the participant to answer the questions	10N Mech • Attach the servo motor to the Arduino • Attach the body of the device to the participant using the Velcro • Attach the squeezing belt at neutral tightness • Screw on cover • Set var = 125; • Press button • Ask the participant to answer the questions	15N Mech • Attach the servo motor to the Arduino • Attach the body of the device to the participant using the Velcro • Attach the squeezing belt at neutral tightness • Screw on cover • Set var = 140; • Press button • Ask the participant to answer the questions

Stroke

3cm/s SMA • Attach the device using the Velcro • Set the power supply to 3V • When the participant is ready turn the power supply on • Turn off after 1,5s/when the movement is complete • Ask the participant to answer the questions	6cm/s SMA • Attach the device using the Velcro • Set the power supply to 4.5V • When the participant is ready turn the power supply on • Turn off after 0.7s/when the movement is complete • Ask the participant to answer the questions	10cm/s SMA • Attach the device using the Velcro • Set the power supply to 8V • When the participant is ready turn the power supply on • Turn off after 0.4s/when the movement is complete • Ask the participant to answer the questions
3cm/s Mech • Ensure the end-effector is extended from the device • Attach the device using the Velcro	6cm/s Mech • Ensure the end-effector is extended from the device • Attach the device using the Velcro	3cm/s Mech • Ensure the end-effector is extended from the device • Attach the device using the Velcro

• Set dis = 60; • Set t = 7900; • Press button • Ask the participant to answer the questions • Press button to extend again	• Set dis = 60; • Set t = 2000; • Press button • Ask the participant to answer the questions • Press button to extend again	• Set dis = 55; • Set t = 1030; • Press button • Ask the participant to answer the questions • Press button to extend again

Messages:

Inviting people to sign up:

Friends:

Hiii schattiesss, zoals jullie weten ben ik al een tijdje bezig met afstuderen en is het nu eindelijk tijd voor gebruikerstestennn ✨ ✨ ✨ En hier heb ik jullie hulp voor nodig! Ik ben opzoek naar parels die naar IO kunnen komen om ongeveer een uur hun mening kunnen geven over haptic sensations. Als je tijd hebt om mij hiermee te helpen heb ik heb hier een linkje waar je een tijdsblok kan kiezen: *link* Dus mocht je tijd en zin hebben kies een moment, je helpt mij er ontzettend mee!

Students:

Hi all! My name is Tanja, I'm an IPD student currently working on my graduation project. I have been working on my project for several weeks and I have now arrived at user testing. In my project, I am working on haptics wearables and specifically the actuation methods for them. I want to look at how users experience the sensations and therefore am conducting user tests. A user test would take place on io and last about an hour. During a test, you will feel different haptic sensations and give your opinion on them. If you would like to help me with this, I would greatly appreciate it. Through this link you can choose a time block that is most convenient for you: *link*

Thanks in advance! Kind regards from Tanja

Message before they arrive

Hoii! Echt heel fijn dat je mij kunt helpen bij mn afstudeerproject 😊 Morgen zal de gebruikerstest in het Materials lab van IO plaatsvinden, maar aangezien dat een beetje verstopt zit kom ik je graag bij de ingang van IO ophalen en dan neem ik je lekker mee

Hello, thank you so much for helping me with my graduation project by participating in my user tests. The user test will happen in the materials lab of industrial design, however as this is a little bit hidden in IDE, I will come to the entrance and bring you there.

Text during test

Hello, thank you so much for participating in my experiment! First let me introduce the test today. Your task is to experience different sensations and give your opinion about them. The user test consists of two sections where two different movements are tested, squeezing and stroking. Within these sections you will feel several different sensations. We will discuss your experience using open questions and you will have to fill out several sematic scale questions. I have designed and built these devices myself, but also tested them extensively on myself. However if at any point you don't feel safe let me know, we will stop using that device or adjust setting. There will be a device fitted to each of your forearms. At first you are not yet allowed to see the devices so you can focus on your experience of the sensation. So that what this contraption is for. First the consent form, let me know if you have any questions.

So lets start, please put your arms through here, so I can attach the devices.

[Attach]

Is it comfi? Okay so we will start with an introduction to the sensation of the X movement. Are you ready, lets feel it:

[Activate one of the device]

Great lets discuss the questions

[Discuss first half of the questions]

Lets feel the second one

[Activate other device]

Okay questions again

[discuss first half again]

Now I am also curios, do you think the sensations were the same or different?

[Last questions]

Great, now you have become familiar with the sensations lets move on. You will now feel a sensation and then fill out a couple semantic scale questions. You can just tell me your answer and I will note them down.

[Sensation] [Google form questions]

[Sensation] [Google form questions]

[Sensation] [Google form questions]

[Sensation] [Google form questions]

Great now I will switch out the devices and we will repeat it again.

[Switch devices]

Are they comfy? Lets go

[Sensation] [Google form questions]

[Sensation] [Google form questions]

[Sensation] [Google form questions]

[Sensation] [Google form questions]

Great, then now its time for you to see the devices and move around.

[Google form design process questions] If a participant wants to feel a sensation again they will have to sit still.

So lets continue to the next phase, the next movement please put your arms through here, so I can attach the devices.

[Attach]

Is it comfi? Okay so we will start with an introduction to the sensation of the X movement. Are you ready, lets feel it:

[Activate one of the device]

Great lets discuss the questions

[Discuss first half of the questions] [notes in word file]

Lets feel the second one

[Activate other device]

Okay questions again

[discuss first half again] [notes in word file]

Now I am also curios, do you think the sensations were the same or different?

[Last questions] [notes in word file]

Great, now you have become familiar with the sensations lets move on. You will now feel a sensation and then fill out a couple semantic scale questions. You can just tell me your answer and I will note them down.

[Sensation] [Google form questions]

[Sensation] [Google form questions]

[Sensation] [Google form questions]

[Sensation] [Google form questions]

Great now I will switch out the devices and we will repeat it again.

[Switch devices]

Are they comfy? Lets go

[Sensation] [Google form questions]

[Sensation] [Google form questions]

[Sensation] [Google form questions]

[Sensation] [Google form questions]

Great, then now its time for you to see the devices and move around.

[Google form design process questions] If a participant wants to feel a sensation again they will have to sit still.

Okay amazing thank you so much for all you feedback so far, the structured part of the interview is now completed. However I am super interested if you have any comments or suggestions for me?

Participant ID: ....

Haptic wearables for Affective touch

This research is conducted as part of the MSc study Industrial Design Engineering at TU Delft. The purpose of this research study is to evaluate the user's experience of several different haptic wearables.

You are being invited to participate in a research study titled comparing actuation methods in haptics wearables. This study is being done by Tanja Overbeek from the TU Delft under supervision of Sepideh Ghodrat.

The purpose of this research study is to discover the user experience of haptic devices using different actuation methods and will take you approximately 60 minutes to complete. The data will be used for a master thesis. We will be asking you to answer questions regarding several experienced sensations through open questions and semantic scale questions.

To the best of our ability your answers in this study will remain confidential. We will minimize any risks by collecting only anonymized data and saving it offline on the researchers laptop.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions.

Researcher: Tanja Overbeek
Contact email: t[redacted]lft.nl
Phone: [redacted]

Informed consent participant

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [*DD/MM/YYYY*], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: • Wearing several haptic devices and experiencing different sensations • Answering open questions and semantic scale questions regarding my experience	☐	☐
4. I understand that the study will end when the master thesis is completed	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
5. I understand that taking part in the study involves the following risk of wearing not CE-certified devices. I understand that these will be mitigated by approval by the HSE advisor ensuring the	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
devices bring no extraordinary risks. Additionally, I am aware that if the devices harm me in any way, I am free to stop at any time.		
6. I understand that the following steps will be taken to minimise the threat of a data breach and protect my identity in the event of such a breach. • All data saved is completely unidentifiable.	☐	☐
7. I understand that personal information collected about me that can identify me, such as my name and email address, will not be shared beyond the study team.	☐	☐
8. I understand that the (identifiable) personal data I provide will be destroyed directly after this study, only unidentifiable data will be saved	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
9. I understand that after the research study the de-identified information I provide will be used for a master thesis, and therefore be saved on the TU Delft repository.	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
10. I give permission for the de-identified answers to be used in the master thesis that I provide to be archived in TU Delft repository so it can be used for future research and learning.	☐	☐
11. I understand that access to this repository is accessible to students and employees of the TU Delft.	☐	☐

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

______________________ ______________________

Last name First name

___ / ___ / 2025 ______________________

Date Signature

Appendix F – Introduction to the sensation

Answers of the participants

Participant ID	P1	
	Squeeze	
	SMA	Mechanical
First impression:	Feels nice	It feels like someone grabbing your wrist
What does it feel like:	Doesnt feel like something from the real world. Like grabbing but in slow motion. Like holding hands but then your wrist.	Someone asking for your attentions to show you something. Look at this!
How does it make you feel	Security, safety. Im here its okay	Yes right, I need to pay attention
Similar or different	The SMA has some sort of delay, Mechanical felt more urgent, SMA was more like, no worries take your time.	
	Stroking	
	SMA	Mechanical
First impression:	Ticklish	Like someone weirdly stroking your arm
What does it feel like:	Like brushing a feather along your arm	It was a vibrating movement, like a really small massage gun maybe
How does it make you feel	It tickles, makes me laugh so happy or amusing	Not necessarily pleasant, difficult, not necessarily chill massage but good for you
Similar or different	The smoothness of the movement was really different, SMA was a smoother movement, Mechanical was more a tapping motion because of the vibration.	

Participant ID	P2	
	Squeeze	
	SMA	Mechanical
First impression:	It was slower, not as instant, slower tightening	Wow that scared me, it was really quick, in one movement really strong
What does it feel like:	Like holding the wrist but for a longer time	Like a person squeezing my wrist
How does it make you feel	Calmer feeling	The noise was not realistic, otherwise it felt fine

Similar or different	SMA was more calming than the mechanical one, both really felt like a good squeeze and not painful	
	Stroking	
	SMA	Mechanical
First impression:	Slower, more pressure, not ticklish which is nice	Interesting, kind of ticklish, very light touch
What does it feel like:	Kind of similar but more firm, arm hairs vs arm, more contact	Like a thumb moving over your arm, or other fingers
How does it make you feel	On the positive side, little bit surprising	Giggels, not annoying, ticklish comfortable
Similar or different	Its different in the sense that the mechanical didnt really touch my arm, SMA was more pressing down	

Participant ID	P3	
	Squeeze	
	SMA	Mechanical
First impression:	Also kind of good, not comparable	Feels like squeezing, but at a weird location. Closer too your hand than the actual wrist, but it feels nice
What does it feel like:	Like putting on a glove and tightening the velcro around the wrist	Like the hand of a child squeezing you
How does it make you feel	Feel fine, niet comforting but okay, not really a big effect	Feels nice, comforting
Similar or different	Feels pretty different, the mechanical is way faster	
	Stroking	
	SMA	Mechanical
First impression:	The other one felt better, little firmer push	Feel like stroking, but more complicated because its also vibrating
What does it feel like:	Like washing yourself but a little harder	No comparison
How does it make you feel	Not really an effect	I like it
Similar or different	SMA was harder, more firm	

Participant ID	P4	
	Squeeze	

	SMA	Mechanical
First impression:	Like a movement from all sides pulling in	Wow the noise scared me a little, it is a fast squeeze, more intense
What does it feel like:	Someone grabbing your hand and squeezing	More complicated to compare, less realistic, noise of the claw machine e
How does it make you feel	Little bit eerie because you don't know what's happening	It scared me, really short and quick
Similar or different	SMA is more realistic, a feeling that I have felt before, Mechanical felt really unknown	
	Stroking	
	SMA	Mechanical
First impression:	Unexpected	Also funny
What does it feel like:	Like a feather along your arm	Reminds me of the checkout belt spinning
How does it make you feel	Happier	Makes me laugh, feels funny
Similar or different	Sensations felt quite different, SMA felt softer, nicer	

Participant ID	P5	
	Squeeze	
	SMA	Mechanical
First impression:	Gives me chicken skin, it was slower and less intense	Bruh hahahah
What does it feel like:	Like the inflatable cuff measuring blood pressure, but slower	Like a inflatable cuff measuring blood pressure, but smaller and quicker, feel like its closing
How does it make you feel	Felt nice, relaxed	Feels nice because it was quick
Similar or different	SMA was slower	
	Stroking	
	SMA	Mechanical
First impression:	It feels ticklish in my finger tips, a cirkling movement, massage machine	Really different, more a stroking motion, but with multiple signals not one smooth movement
What does it feel like:	Massage machine	Like a soft toothbrush moving over your skin

How does it make you feel	Ticklish, long term probably nice	Fine, but not like wow
Similar or different	Different, SMA more like a massage, more pressure or stronger, Mechanical felt more like stroking	

Participant ID	P6	
	Squeeze	
	SMA	Mechanical
First impression:	Ooh it gets warm. More calm, friendlier, really quiet, really slow, slow release, not such an abrupt release, friendly	Wow the noise, it was really short, quick squeeze, kind of abrupt, still tingles in my fingers after, the sides of my wrist felt squeezed
What does it feel like:	Like a hair elastic thats just a little too tight and then removing it	Like the leash of your dog is around your wrist and the dog suddenly runs away and returns again quickly
How does it make you feel	Feels nice, content	A little surprised otherwise fine
Similar or different	Mechanical feels heavier, SMA more light sensation for feels nicer	
	Stroking	
	SMA	Mechanical
First impression:	Oh very cute, short distance, kind of confused	Longer movement, maybe feels more because of the location, feel wider
What does it feel like:	Like the swipe of a finger, really short cut of movement, first date vibes kind of touch	A comforting stroke, or a lick of a dog
How does it make you feel	Wanting more	Feels nice, relaxed
Similar or different	Mechanical you can enjoy, longer duration and more contact area, SMA feels abrupt and then the feeling kind of stuck around. Mechanical is more relaxed	

Participant ID	P7	
	Squeeze	
	SMA	Mechanical
First impression:	Wow	Scared by the noise, really abrupt, noisy

What does it feel like:	Like the inflatable cuff for measuring blood pressure around your arm	No clue for a second, what is happening to me
How does it make you feel	Relieved	Fine
Similar or different	SMA felt a lot more pleasant because it was more gradual, Mechanical felt really coarse, bam bamm	
	Stroking	
	SMA	Mechanical
First impression:	Feels like brushing with a feather, feels narrow	Reaally weird, back and forth movement and a some rotating
What does it feel like:	Like a feather, really light contact	A round toothbrush along your arm
How does it make you feel	Such a light feeling, did really make an impact	Not soft, but also not annoying
Similar or different	SMA felt really light and short, Mechanical felt longer more extensive	

Participant ID	P8	
	Squeeze	
	SMA	Mechanical
First impression:	Not that nice, felt weird, it contracted and spun	Contracting, strap tighten and then returned, movement back felt different
What does it feel like:	Felt like my wrist was being squeeze and rolled around, like my wrist was a dough ball	Like a pointer rotating back with the central point right above my wrist
How does it make you feel	Never felt this before, surprised	Nothing special but a clear sensation
Similar or different	Really different, mechanical was more spontaneous, SMA softer and more gradual build up and winding down, mechanical a quick pulse, SMA you could miss	
	Stroking	
	SMA	Mechanical
First impression:	Dirty feeling, not really nice, maybe due to humanlikeness, therefore chills, but not necessarily bad	Familiar feeling, vibrating phone recognisable, getting used to the tests too. Wow what
What does it feel like:	Finger along the outside of your wrist that is cold	Phone vibration
How does it make you feel	Unfamiliar	Fine

Similar or different	Not at all the same, mechanical very machine-like, more abrupt pulse-like, SMA is build-up and build-down	

Participant ID	P9	
	Squeeze	
	SMA	Mechanical
First impression:	Same as previous but less annoying, tensing up. It gets warm	Weird, strange, mechanical
What does it feel like:	Hair elastic around your arm that pulls tighter, no sound is nice, only feeling and not also sound	Like going into an MRI scan in a hospital, almost alien-like, camera shutter sound
How does it make you feel	Slightly irritated	Not necessarily pleasant, not terribly affected by it, but not top notch either, stress feeling almost, urgency squeeze
Similar or different	SMA is smoother, progression smooth, mech goes very suddenly, abruptly and the sound is intense	
	Stroking	
	SMA	Mechanical
First impression:	Unexpected, Small move, movement back feels very special	It vibrates
What does it feel like:	A finger tapping you, not really a stroke, Occasionally more pressure on my arm	Reminds me of the satisfier, electrical toothbrush, something you tap/vibrate but not something sharp
How does it make you feel	Pretty neutral, don't feel very stroked	Giggly, ticklish, ticklish feeling
Similar or different	SMA felt human, speed is quite different, SMA more longer intervals felt more like a stroke, Mech felt bit like fast ticking	

Participant ID	P10	
	Squeeze	
	SMA	Mechanical
First impression:	Warmth, also feels one side contract a bit more than other sides, jacket with a belt	Same movement, also squeezing, but a bit more direct/sudden

	around your waist and that's quite nice, not too intense but comfi	
What does it feel like:	Reminds me of the blood pressure band, or band to go with your jacket	Robotic, very quick to contract your chapucon too much
How does it make you feel	Actually quite nice	Less chill, think also because of the sound, less natural
Similar or different	SMA like a hand is squeezing you, Mech not really, What they do is almost the same but you do feel they are built differently, Mech is jerkier and the sound feels less natural	
	Stroking	
	SMA	Mechanical
First impression:	Also tickled because it goes along your hair like that, very soft, soft touch are often a bit irritating	Laughing, tickling, Felt like something was spinning, back and forth but not very far, spinning
What does it feel like:	Accidentally sweeping past a person, to swoosh past them and then accidentally touching them anyway	Reminds me of putting your phone on your arm and then vibrate function
How does it make you feel	Neutral, slightly ticklish	Would like to tickle, hair gets caught
Similar or different	Mech is a bit more jerky, Both though ticklish, just soft, not the favorite touch	

Participant ID	P11	
	Squeeze	
	SMA	Mechanical
First impression:	Well fine, not unpleasant just good	Wohh, sound is bad, little unpleasant sound more unpleasant than feeling, at once a lot of power
What does it feel like:	Like someone squeezing your wrist	Also someone squeezing you, blood pressure band
How does it make you feel	Fine	Unpleasant
Similar or different	SMA is nice, natural, Mech is really a device	
	Stroking	

	SMA	Mechanical
First impression:	Very light, chill, relaxed	Ugh, apart, vibration, tickles
What does it feel like:	Being stroked, a little pet	Vibrator
How does it make you feel	Fine	Cheery
Similar or different	SMA more pleasant, less intense, less pressure, softer touch	

Participant ID	P12	
	Squeeze	
	SMA	Mechanical
First impression:	Slightly more of a sort tingle, much slower, held longer, seems less harsh	Very soft and sweet, but makes a lot of noise, most at the top
What does it feel like:	Snake wrapped around your wrist that tightens, Never experienced it, more gradually so a kind of muscle	Blood pressure meters, but squeeze less hard
How does it make you feel	Fine	Well more because you don't know what's going to happen, so bit surprising
Similar or different	Obvious difference, that sound especially very different	
	Stroking	
	SMA	Mechanical
First impression:	Like a brush goes over your arm, stays a little tingly when moving back, not fluffy movement, crawling back feels weird and not soft	Does not feel like stroking but pushed touch, feels quite rough
What does it feel like:	Brush	Lollipop over your skin, bit stiff, not even surface, don't stroke but push it
How does it make you feel	Unexpected sensation but not worrying, crawling back is weird	Fine, but not necessarily very pleasant
Similar or different	Mech feels a bit obligatory, SMA feels like it has a different purpose, want to make stroke, Mech is more without amplitude, whole movement equally hard, no build-up of pressure	

Participant ID	P13	
	Squeeze	
	SMA	Mechanical
First impression:	T was very constant pressure increase though, very gradual, similar to other hand, but less sudden	Squeezing, sound makes it seem more aggressive, but doesn't hurt
What does it feel like:	Kind off like, someone who gently grabs your wrist with two fingers	Like someone closing their fingers around your wrist
How does it make you feel	Good, not very unpleasant	Fine, sort of not very strong emotion, but a little bit of shock reaction
Similar or different	Especially the speed is really different, and the sound, SMA feels more human, it's kind of the same power and intensity though	
	Stroking	
	SMA	Mechanical
First impression:	Soft, did not feel cold material, ticklishly tingly	Almost a bit trippy, lots of different movements side by side, also kind of soft, felt almost bit static loaded
What does it feel like:	Carpet, guinea pig walking along your arm, something moving	ge or fabric, irregular, kind of massage chair, very small on your arm
How does it make you feel	Unknown what was going to happen, not negative, but not very strong reaction either, just very curious, nice feeling though	Kind of fun, kind of nice
Similar or different	Texture kind off similar, pressure on skin also, movement is different, SMA was bit predictable and the Mech felt more random in movement direction, speed pretty similar	

Participant ID	P14	
	Squeeze	
	SMA	Mechanical
First impression:	It was gentle, stronger, and more abrupt	Worse, it was more artificial, the noise is horrible, less organic,

		really straightforward open and close
What does it feel like:	Maybe someone wrapping their arm around the wrist, firm but gentle grab	A car window opening and closing, noise and not continuous movement, not the feeling around the wrist
How does it make you feel	Same feeling, maybe because of the test, maybe on the street more alert, more attention	The feeling is the same, not really affected now, but asking to pay attention but more confused
Similar or different	Really, SMA super natural feels like something that can happing in real life, natural feeling, Mech is machine and artificial, maybe same function but feeling is different, imagining the motors and gears	
	Stroking	
	SMA	Mechanical
First impression:	Also gentle, similar movement, a bit stronger, relaxing	Gentle,
What does it feel like:	Feeling is the same, someone touching your arm	When someone touches your arm, very friendly
How does it make you feel	Relaxed	Relaxed
Similar or different	Very similar, maybe the noise again, but less prominent already forgot almost	

Participant ID	P15	
	Squeeze	
	SMA	Mechanical
First impression:	Much firmer than expected, and hold me too, unexpectedly, felt more gradual, holding first and then firmer, more uniform, whole wrist gradually experiencing pressure	Very abrupt, quite intense, robot-like, not necessarily hard or painful but not pleasant either
What does it feel like:	Inflate blood pressure band gradually	As if suddenly grabbed against your will
How does it make you feel	Okay, surprised by the strength though, feels relatively harder	Glad it doesn't happen in my daily life

Similar or different	SMA harder, firmer, but comfotabler, much more gradual, felt comfotable as a weigted blanked	
	Stroking	
	SMA	Mechanical
First impression:	Much more organic, movement back is really special, movement back tickles, very much a bug, kind off freaky, more engaging, not predictable, more deliberate	Does feel like a stroke, quite noticeable, stands out, not necessarily uncomfortable but not something you feel often, thought it would feel more uncomfortable, but feels okay
What does it feel like:	Back movement like an insect, taking off bracelet	Bug running down my arm when you least expect it
How does it make you feel	Forward movement curious, Backward movement slightly tense	A lot more aware, more alert
Similar or different	Very differently, Mech very much on off and movement very consistent, SMA organically faster then slower again.	

Participant ID	P16	
	Squeeze	
	SMA	Mechanical
First impression:	Squeezes the wrist slightly	Wow, much faster, intensely fast
What does it feel like:	Sort of by the doctor heart rate meter	Heart rate measuring band, but faster, someone squeezing my wrist
How does it make you feel	Not a big deal, thinking of doctor	Feels okay, someone pinch me for a moment
Similar or different	Mech is much faster, SMA feels like something is getting smaller and Mech feels like something is being squeezed together	
	Stroking	
	SMA	Mechanical
First impression:	Softer than the other, rolls over the arm	Really funny, tickles

What does it feel like:	Pencil rolling over my arm	Phone vibrating in your pocket but on your arm
How does it make you feel	Not as funny as the other, just neutral	Funny, laugh
Similar or different	Mech is more with vibration, SMA rolls over the arm	

Participant ID	P17	
	Squeeze	
	SMA	Mechanical
First impression:	Much slower, felt more intense, warmth	Wow, very different, switch gears for a moment,
What does it feel like:	Someone slowly, increasingly squeezing harder	Feels like someone is squeezing my wrist, firm squeeze
How does it make you feel	Less, fine but more negative	As if someone wants attention from me
Similar or different	Quite different, Mech feels more like someone is drawing attention for a moment, SMA feels more like they are squeezing with vicious intention	
	Stroking	
	SMA	Mechanical
First impression:	Much softer than the other, anyway a different place	Ticklish
What does it feel like:	Difficult to compare	Feels like someone is stealing me
How does it make you feel	Feels fine	Yes, kind of nice
Similar or different	Pretty different, SMA feels when a hand goes over you like a stroke, Mech more like a sort of squeeze	

Participant ID	P18	
	Squeeze	
	SMA	Mechanical
First impression:	Was a gentle feeling, quiet, a squeezing sensation but very subtle, really not painful	More aggressive, less pleasant
What does it feel like:	Tighten the strap of your watch a hole	Like someone squeezing your wrist, not painful but less pleasant

How does it make you feel	Fine, not annoying	Bit uncomfortable
Similar or different	Really different, SMA softer and tender and more pleasant, Mech was more aggressive, SMA was build-up and Mech was a short sensation	
	Stroking	
	SMA	Mechanical
First impression:	Did feel like a movement from one place to another	Did tickle a bit, not necessarily like a human tickles you but slightly
What does it feel like:	With a serrated edge rolling over your arm, little thumb massage	Stroking a hard feather across your arm
How does it make you feel	Postive not unpleasant	Didn't find it unpleasant, is tickling pleasant or not
Similar or different	Mech tickled more, SMA was more subtle	

Participant ID	P19	
	Squeeze	
	SMA	Mechanical
First impression:	Like a balloon being inflated, but pleasant, calming. It gets warm in a nice way	Wtf that sound, immediately felt extreme, feeling fine though, sound concerns
What does it feel like:	Balloon	Like pulling a tyrap on your wrist,
How does it make you feel	Soothing, pretty nice	Sound worrisome, sensation was fine
Similar or different	Same family but more different than the stroke sensation, SMA more soothing and subtle, Mech sound	
	Stroking	
	SMA	Mechanical
First impression:	The other a bit more pleasant, location is in a different place, smartwatch vibes, idea of the smartwatch not pleasant, unexpected place	Vibration, fine
What does it feel like:	De smartwatch	Phone ringing
How does it make you feel	Just a little less pleasant	Fine
Similar or different	Feels different but in the same group, vibration is different, attracting attention in a different way	

Participant ID	P20	
	Squeeze	
	SMA	Mechanical
First impression:	More unpleasant, you just don't touch it but you kind off of feel it, chills, very slow build-up and tingle lingers a bit	Wow, startled, unexpected movement
What does it feel like:	Very gentle stroking, too gentle, a squeeze but too weak	Blood pressure meter but very weak
How does it make you feel	Just a little unpleasant	Neutral
Similar or different	Different, Mech was more pleasant, shorter, faster, instant, SMA slow build less pleasant	
	Stroking	
	SMA	Mechanical
First impression:	Little, very short	Vibrating I feel almost more than stroking
What does it feel like:	Relatively large insect that sits on your arm and then flies away	Long blades of grass in the forest you walk past
How does it make you feel	Pretty okay	Neutral, not that strong feeling
Similar or different	Very different, one is on the length of your arm, other sideways, SMA towards hand and Mech sideways, Mech felt more times back and forth SMA I once woosh	

Participant ID	P21	
	Squeeze	
	SMA	Mechanical
First impression:	Wojo, build up, kinder, also make as if you are putting on swimming bands, more time to think about it	Intense, wow sound, present, not necessarily friendly
What does it feel like:	Inflating swimming bands	Doesn't feel like anything at all
How does it make you feel	Also attentive, feeling that something is happening, nice way of building up in the touch	Fine, but not necessarily good, though alert
Similar or different	Different, Mech very abrupt and sound a bit more mechanical, SMA because of the buildup a bit friendlier	
	Stroking	
	SMA	Mechanical
First impression:	Unexpected, but sweet, light	Felt more than the sma, but maybe also more

		conscious, also felt the return very much, clear stroke
What does it feel like:	A light touch of a human being	A stroke from a human being
How does it make you feel	More also the setting, just funny, a touch, you're paying attention	Good, same as the SMA
Similar or different	Mech is a bit more present, felt more, moved faster, also the returned very clearly	

Participant ID	P22	
	Squeeze	
	SMA	Mechanical
First impression:	Not intense very subtle	Especially the sound I hear, less subtly, oh what is happening
What does it feel like:	Gently tap something	Nothing comparable
How does it make you feel	No impact	Confusing
Similar or different	Quite different, SMA felt much more subtle than mech	
	Stroking	
	SMA	Mechanical
First impression:	Less intense but still not chill, itchy	Nasty, just weird feeling, itchy
What does it feel like:	Maybe like pulling your shirt over your arm, little bit of clothing along your arm	Bit like being tickled, but not quite
How does it make you feel	Not super chill, but better than the others	Not pleasant
Similar or different	SMA is more natural, and therefore less annoying but still not chill	

Squeeze SMA actuation

Thematic analysis

Sensory effect

- Calming
- Soothing and subtle
- No worries
- Calming feeling
- Soothing
- Weighted blanked
- Secure, safe
- Content
- Relaxing
- Relieved
- Surprised
- Surprised
- Squeezed and rolled around
- Little negative
- Visous
- Slightly irritating
- Unpleasant slow buildup
- Little bit unpleasant

Movement

- Constant increasing pressure, gradual
- Slower movement, held longer
- Kind build-up
- Smooth
- Slower movement
- Slower but intense
- Slow motion grab
- Slow tightning
- Gradual pleasant
- increasingly hard squeeze
- Soft and gradual
- Unpleasant slow buildup

Perceived intention

- Gentle
- Comfortable gradual
- Calming, friendly
- Gentle, subtle squeeze
- Subtle gentle tap
- Friendlier
- Comfortable

Actuation consequence

- Gets warm
- Oh warmth
- Warm in a nice way
- It gets a little warm

Intensity

- Too weak for a squeeze
- Soft and tender
- Light sensation
- Firm but gentle grab

Similarity

- Natural
- Someone grabbing your hand
- Holding wrist for a long time
- Firm long hold
- Gentle grab with two fingers
- Like a hand
- Natural feeling
- Human
- Realistic
- Inflating balloon
- Hair elastic
- Blood measuring band
- Blood measuring band
- Hair elastic
- Tightning velcro around the wrist
- Swimming floaties
- Blood measuring band
- Wrist band
- Blood measuring band
- Blood measuring band


Squeeze Mechanical actuation
Perceived intention
Aggressive unpleasant
Not calming
Aggressive
Not friendly
Worried
Unpleasant
Little bit stressful
uncomfortable
Confusing
Soft and sweet
Intensity
Really firm squeeze
Intense
Movement
Short sensation
Quick and nice
Quick strong movement
High speed
Fast intense
Fast
Similarity
Weird, stange
Jerky, not natural
Unknown
Hospital vibes
Artificial, not organic
Not realistic, noisy
Robotic, quick
Really a device
motors and gears
Unrealistic
Not humanlike
Someone closing fingers around wrist
Child hand squeezing
Being grabbed
Sudden grab against your will
Aggressive squeeze by someone
Dog leash tightning suddenly
Blood measuring band
Blood measuring band
Blood pressure band
Ty-rap around the wrist
Blood pressure band
Blood pressure band
Scary
Shock
Scary
Startled unexpected
Pleasant short and fast
Comforting
Sensory effect
Squeeze for attention
Alert
Got to pay attention
Urgent
Pay attention
Drawing attention
Sudden, abrupt
Surprising
Direct sudden movement
Abrupt intense
Abrupt
Abrupt
Spontaneous
Very sudden, bam bam
Mechanical consequences
Noisy
Scared by the noise
Intense sound
Bad sound
Noise
Noise
Noise
Sound was extreme
Sound is not subtle

Strokimg SMA actuation

Similarity

Hand stroking
Light touch by a human
Being stroked
Washing your arm
A deliberate stroke
Human
Natural
Cold finger along the wrist
Surprising
Unfamiliar
Special feeling
Confused
Soft paint brush
Feather
An insect taking off from your arm
Shirt along your arm
Feather
Like a guinea pig brushing along the arm
Insect flying away
Feather

Effect of the sensation

Tickled
Chills
Ticklish
Ticklish
Ticklish
Curious
Positive
Positive side
Happy, funny
Happier
Wanting more
Curious

Movement

Organic movement
Rolling a ribbed thing
Soft, rolling
Buildup and down
Speeding up and slowing down organically
One smooth movement
Smooth movement
Predictable
deliberate

Perceived intention

Feels short, cut off
Annoyingly soft touch
Cut off swipe of a finger
Accidental touch
Subtle
Gentle grabbing attention
Pleasant soft
Light feeling
Soft
Softer, nicer
Sweet
Relaxed
Gentle relaxing
Softer
Cute, short

Intensity

More pressure
Pleasant
Firmer push


Stroking Mechanical actuation
Similarity
Thumb along the arm
Somebody taking me away
Human touch
Real stroking
Spinning checkout belt
Bug running along the arm
Multiple signals
Toothbrush
Electrical toothbrush
Lick of a dog
Blades of long grass along your arm
Toothbrush
Rough surface stroked
Trippy lots of seperate touches
Massage gun
Firm feather
Field of soft flowers
Mechanical consequences
Vibration
Vibrations
Vibration
Tapps
Vibration
Vibrating phone
Phone vibration
Tapping motion
Vibrations
Ringing phone
Movement
Consistent movement
Weird stroking
Jerky
Weird feeling
Weird
Complicated
Random movements
Weird rotating movement
Intensity
Intense
More present movement
Pushed touch
Extensive movement
Clear stroke
Enjoy longer movement
Perceived intention
Gentle
Relaxed
Relaxed
Comforting stroke
Friendly
Necessary but uncomfortable massage
Annoying
Obligatory
Effect of the sensation
Non human tickle
Ticklish
Ticklish
Tickled
Ticklish
Very noticable
Urgent attention
Alert
Machine like, abrupt

Appendix G – Semantic differential scale answers

Tijdstempel	Participant (P1/P30)	Which device sensation	Actuation	Variation	Pleasantness	Intensity	Human-likeness	Force or Speed	Tone
3-5-2025 10:21:20	P1	Squeeze	SMA	Low (5N or 3cm/s)	5	2	3	2	6
3-5-2025 10:24:11	P1	Squeeze	Mechanics	Low (5N or 3cm/s)	3	6	6	6	2
3-5-2025 10:26:51	P1	Squeeze	SMA	High (15N or 10cm/s)	4	5	5	5	4
3-5-2025 10:28:55	P1	Squeeze	Mechanics	High (15N or 10cm/s)	2	6	5	5	1
3-5-2025 10:36:33	P1	Squeeze	Mechanics	Low (5N or 3cm/s)	4	5	6	5	4
3-5-2025 10:38:10	P1	Squeeze	SMA	High (15N or 10cm/s)	3	2	5	6	4
3-5-2025 10:39:30	P1	Squeeze	Mechanics	High (15N or 10cm/s)	4	1	5	1	5
3-5-2025 10:40:34	P1	Squeeze	SMA	Low (5N or 3cm/s)	6	1	2	1	5
3-5-2025 11:00:01	P1	Stroking	Mechanics	Low (5N or 3cm/s)	3	4	2	3	4
3-5-2025 11:01:00	P1	Stroking	SMA	Low (5N or 3cm/s)	5	2	5	5	6
3-5-2025 11:01:56	P1	Stroking	Mechanics	High (15N or 10cm/s)	4	5	4	6	4
3-5-2025 11:03:17	P1	Stroking	SMA	High (15N or 10cm/s)	5	5	6	4	5
3-5-2025 11:07:51	P1	Stroking	SMA	High (15N or 10cm/s)	6	5	6	4	5
3-5-2025 11:09:34	P1	Stroking	Mechanics	High (15N or 10cm/s)	3	5	4	6	4
3-5-2025 11:11:52	P1	Stroking	SMA	Low (5N or 3cm/s)	5	3	5	2	5
3-5-2025 11:12:47	P1	Stroking	Mechanics	Low (5N or 3cm/s)	3	4	2	5	4
3-5-2025 12:00:26	P2	Stroking	Mechanics	High (15N or 10cm/s)	5	2	3	6	6
3-5-2025 12:02:17	P2	Stroking	SMA	Low (5N or 3cm/s)	5	4	2	7	6
3-5-2025 12:03:45	P2	Stroking	Mechanics	Low (5N or 3cm/s)	6	3	3	5	7
3-5-2025 12:05:07	P2	Stroking	SMA	High (15N or 10cm/s)	5	4	3	6	6
3-5-2025 12:09:59	P2	Stroking	SMA	Low (5N or 3cm/s)	6	4	5	6	6
3-5-2025 12:10:57	P2	Stroking	Mechanics	High (15N or 10cm/s)	4	3	2	5	4
3-5-2025 12:11:55	P2	Stroking	SMA	High (15N or 10cm/s)	4	3	3	5	5
3-5-2025 12:13:00	P2	Stroking	Mechanics	Low (5N or 3cm/s)	5	4	3	3	5
3-5-2025 12:27:06	P2	Squeeze	SMA	High (15N or 10cm/s)	6	6	6	6	5
3-5-2025 12:28:14	P2	Squeeze	Mechanics	Low (5N or 3cm/s)	3	5	3	5	4
3-5-2025 12:29:32	P2	Squeeze	SMA	Low (5N or 3cm/s)	4	2	5	2	5
3-5-2025 12:30:26	P2	Squeeze	Mechanics	High (15N or 10cm/s)	5	2	3	2	5
3-5-2025 12:35:37	P2	Squeeze	Mechanics	High (15N or 10cm/s)	3	6	3	6	2
3-5-2025 12:36:23	P2	Squeeze	SMA	Low (5N or 3cm/s)	5	3	6	3	5
3-5-2025 12:37:07	P2	Squeeze	Mechanics	Low (5N or 3cm/s)	5	5	3	5	6
3-5-2025 12:37:52	P2	Squeeze	SMA	High (15N or 10cm/s)	6	5	6	6	5
3-5-2025 13:42:25	P3	Stroking	SMA	High (15N or 10cm/s)	6	5	6	3	6
3-5-2025 13:44:37	P3	Stroking	Mechanics	High (15N or 10cm/s)	5	4	4	7	4
3-5-2025 13:46:10	P3	Stroking	SMA	Low (5N or 3cm/s)	6	6	6	4	5
3-5-2025 13:47:41	P3	Stroking	Mechanics	Low (5N or 3cm/s)	3	6	2	4	4
3-5-2025 13:50:50	P3	Stroking	Mechanics	Low (5N or 3cm/s)	7	5	6	3	7
3-5-2025 13:52:03	P3	Stroking	SMA	High (15N or 10cm/s)	6	6	7	3	6
3-5-2025 13:53:21	P3	Stroking	Mechanics	High (15N or 10cm/s)	5	3	3	6	4
3-5-2025 13:54:49	P3	Stroking	SMA	Low (5N or 3cm/s)	6	6	6	3	7
3-5-2025 14:09:07	P3	Squeeze	Mechanics	High (15N or 10cm/s)	6	6	7	6	7
3-5-2025 14:10:42	P3	Squeeze	SMA	Low (5N or 3cm/s)	4	4	3	3	4
3-5-2025 14:12:03	P3	Squeeze	Mechanics	Low (5N or 3cm/s)	5	5	5	6	6
3-5-2025 14:13:31	P3	Squeeze	SMA	High (15N or 10cm/s)	7	6	6	6	7
3-5-2025 14:20:53	P3	Squeeze	SMA	Low (5N or 3cm/s)	4	2	2	2	4
3-5-2025 14:21:45	P3	Squeeze	Mechanics	Low (5N or 3cm/s)	2	7	6	7	2
3-5-2025 14:22:54	P3	Squeeze	SMA	High (15N or 10cm/s)	3	5	5	6	4
3-5-2025 14:24:02	P3	Squeeze	Mechanics	High (15N or 10cm/s)	3	5	3	6	3
3-5-2025 15:30:37	P4	Squeeze	Mechanics	High (15N or 10cm/s)	2	3	1	2	3
3-5-2025 15:31:53	P4	Squeeze	SMA	High (15N or 10cm/s)	4	2	5	2	6
3-5-2025 15:32:45	P4	Squeeze	Mechanics	Low (5N or 3cm/s)	3	5	3	5	4
3-5-2025 15:33:44	P4	Squeeze	SMA	Low (5N or 3cm/s)	4	1	5	1	7
3-5-2025 15:39:47	P4	Squeeze	SMA	High (15N or 10cm/s)	4	1	5	1	6
3-5-2025 15:40:52	P4	Squeeze	Mechanics	High (15N or 10cm/s)	2	3	2	4	2
3-5-2025 15:41:41	P4	Squeeze	SMA	Low (5N or 3cm/s)	5	1	5	1	6
3-5-2025 15:42:20	P4	Squeeze	Mechanics	Low (5N or 3cm/s)	4	3	4	3	4
3-5-2025 15:56:36	P4	Stroking	SMA	High (15N or 10cm/s)	4	2	3	2	5
3-5-2025 15:57:41	P4	Stroking	Mechanics	High (15N or 10cm/s)	4	3	3	4	4
3-5-2025 15:58:37	P4	Stroking	SMA	Low (5N or 3cm/s)	5	1	3	1	5
3-5-2025 15:59:25	P4	Stroking	Mechanics	Low (5N or 3cm/s)	5	5	3	3	4
3-5-2025 16:01:15	P4	Stroking	Mechanics	Low (5N or 3cm/s)	4	4	1	3	3
3-5-2025 16:01:56	P4	Stroking	SMA	Low (5N or 3cm/s)	3	2	3	5	2
3-5-2025 16:02:48	P4	Stroking	Mechanics	High (15N or 10cm/s)	5	3	4	5	6
3-5-2025 16:04:08	P4	Stroking	SMA	High (15N or 10cm/s)	3	3	3	3	2
3-6-2025 11:45:02	P5	Stroking	Mechanics	Low (5N or 3cm/s)	5	3	3	4	7
3-6-2025 11:47:17	P5	Stroking	SMA	Low (5N or 3cm/s)	6	3	5	2	7
3-6-2025 11:48:14	P5	Stroking	Mechanics	High (15N or 10cm/s)	3	5	2	5	5
3-6-2025 11:49:42	P5	Stroking	SMA	High (15N or 10cm/s)	6	3	6	4	7
3-6-2025 11:54:34	P5	Stroking	Mechanics	Low (5N or 3cm/s)	6	3	5	3	5
3-6-2025 11:55:37	P5	Stroking	SMA	Low (5N or 3cm/s)	6	2	6	2	6
3-6-2025 11:56:37	P5	Stroking	Mechanics	High (15N or 10cm/s)	4	7	3	7	4
3-6-2025 11:57:39	P5	Stroking	SMA	High (15N or 10cm/s)	6	3	6	2	7
3-6-2025 12:14:20	P5	Squeeze	SMA	High (15N or 10cm/s)	6	4	5	5	5
3-6-2025 12:15:24	P5	Squeeze	Mechanics	High (15N or 10cm/s)	4	5	6	6	3
3-6-2025 12:16:27	P5	Squeeze	SMA	Low (5N or 3cm/s)	4	1	4	1	6
3-6-2025 12:17:28	P5	Squeeze	Mechanics	Low (5N or 3cm/s)	5	4	6	4	4
3-6-2025 12:23:54	P5	Squeeze	SMA	Low (5N or 3cm/s)	5	2	3	2	6
3-6-2025 12:26:16	P5	Squeeze	Mechanics	High (15N or 10cm/s)	3	6	5	6	3
3-6-2025 12:27:15	P5	Squeeze	SMA	High (15N or 10cm/s)	6	4	6	5	7
3-6-2025 12:28:12	P5	Squeeze	Mechanics	Low (5N or 3cm/s)	5	5	5	5	4
3-6-2025 13:48:38	P6	Squeeze	SMA	Low (5N or 3cm/s)	4	1	2	1	7
3-6-2025 13:50:15	P6	Squeeze	Mechanics	High (15N or 10cm/s)	5	5	6	5	3
3-6-2025 13:52:43	P6	Squeeze	SMA	High (15N or 10cm/s)	6	5	6	5	5
3-6-2025 13:54:20	P6	Squeeze	Mechanics	Low (5N or 3cm/s)	5	3	5	5	6
3-6-2025 14:02:35	P6	Squeeze	SMA	High (15N or 10cm/s)	3	7	5	7	2
3-6-2025 14:04:14	P6	Squeeze	Mechanics	Low (5N or 3cm/s)	7	4	6	5	6
3-6-2025 14:05:44	P6	Squeeze	SMA	Low (5N or 3cm/s)	6	3	3	3	4
3-6-2025 14:08:49	P6	Squeeze	Mechanics	High (15N or 10cm/s)	7	5	5	3	5
3-6-2025 14:30:36	P6	Stroking	SMA	High (15N or 10cm/s)	4	5	3	7	3
3-6-2025 14:31:55	P6	Stroking	Mechanics	Low (5N or 3cm/s)	6	6	6	3	5
3-6-2025 14:33:14	P6	Stroking	SMA	Low (5N or 3cm/s)	5	5	5	5	5
3-6-2025 14:34:26	P6	Stroking	Mechanics	High (15N or 10cm/s)	3	3	2	6	5
3-6-2025 14:36:42	P6	Stroking	Mechanics	High (15N or 10cm/s)	3	3	2	6	3
3-6-2025 14:38:03	P6	Stroking	SMA	High (15N or 10cm/s)	6	5	6	5	5
3-6-2025 14:39:07	P6	Stroking	Mechanics	Low (5N or 3cm/s)	6	6	7	3	6
3-6-2025 14:40:33	P6	Stroking	SMA	Low (5N or 3cm/s)	5	5	3	5	5
3-6-2025 15:35:42	P7	Stroking	SMA	Low (5N or 3cm/s)	4	3	4	4	5
3-6-2025 15:37:13	P7	Stroking	Mechanics	High (15N or 10cm/s)	4	4	2	5	4
3-6-2025 15:38:59	P7	Stroking	SMA	High (15N or 10cm/s)	5	3	5	3	5
3-6-2025 15:39:55	P7	Stroking	Mechanics	Low (5N or 3cm/s)	3	3		2	3
3-6-2025 15:42:48	P7	Stroking	Mechanics	High (15N or 10cm/s)	5	5	3	5	4
3-6-2025 15:44:11	P7	Stroking	SMA	Low (5N or 3cm/s)	6	4	4	4	5
3-6-2025 15:45:18	P7	Stroking	Mechanics	Low (5N or 3cm/s)	4	3	3	2	4
3-6-2025 15:46:14	P7	Stroking	SMA	High (15N or 10cm/s)	5	3	4	5	5
3-6-2025 16:04:18	P7	Squeeze	Mechanics	Low (5N or 3cm/s)	4	5	3	5	3
3-6-2025 16:05:59	P7	Squeeze	SMA	Low (5N or 3cm/s)	5	2	5	2	6
3-6-2025 16:07:29	P7	Squeeze	Mechanics	High (15N or 10cm/s)	4	4	3	4	4
3-6-2025 16:08:45	P7	Squeeze	SMA	High (15N or 10cm/s)	5	5	3	5	4

3-6-2025 16:13:40 P7	Squeeze	Mechanics	High (15N or 10cm/s)	3	5	3	5	3
3-6-2025 16:14:48 P7	Squeeze	SMA	High (15N or 10cm/s)	5	3	5	3	5
3-6-2025 16:15:58 P7	Squeeze	Mechanics	Low (5N or 3cm/s)	3	4	3	5	3
3-6-2025 16:17:11 P7	Squeeze	SMA	Low (5N or 3cm/s)	6	4	5	2	5
3-6-2025 17:25:55 P8	Squeeze	Mechanics	Low (5N or 3cm/s)	4	2	1	3	2
3-6-2025 17:31:58 P8	Squeeze	SMA	Low (5N or 3cm/s)	4	1	6	1	5
3-6-2025 17:33:13 P8	Squeeze	Mechanics	High (15N or 10cm/s)	3	6	1	5	2
3-6-2025 17:34:34 P8	Squeeze	SMA	High (15N or 10cm/s)	5	2	3	2	6
3-6-2025 17:39:47 P8	Squeeze	SMA	High (15N or 10cm/s)	6	2	6	1	6
3-6-2025 17:41:41 P8	Squeeze	Mechanics	Low (5N or 3cm/s)	3	5	1	4	3
3-6-2025 17:42:58 P8	Squeeze	SMA	Low (5N or 3cm/s)	5	2	5	1	5
3-6-2025 17:44:05 P8	Squeeze	Mechanics	High (15N or 10cm/s)	2	6	1	2	2
3-6-2025 17:57:55 P8	Stroking	SMA	High (15N or 10cm/s)	6	2	7	1	7
3-6-2025 17:59:28 P8	Stroking	Mechanics	High (15N or 10cm/s)	3	5	2	6	3
3-6-2025 18:00:22 P8	Stroking	SMA	Low (5N or 3cm/s)	5	3	6	2	4
3-6-2025 18:01:29 P8	Stroking	Mechanics	Low (5N or 3cm/s)	4	5	3	6	3
3-6-2025 18:04:18 P8	Stroking	SMA	Low (5N or 3cm/s)	5	1	6	1	6
3-6-2025 18:05:31 P8	Stroking	Mechanics	Low (5N or 3cm/s)	4	3	1	4	5
3-6-2025 18:06:24 P8	Stroking	SMA	High (15N or 10cm/s)	6	1	6	5	6
3-6-2025 18:08:08 P8	Stroking	Mechanics	High (15N or 10cm/s)	4	3	2	4	4
3-7-2025 10:23:14 P9	Stroking	Mechanics	High (15N or 10cm/s)	3	5	1	6	2
3-7-2025 10:24:24 P9	Stroking	SMA	Low (5N or 3cm/s)	5	4	6	4	6
3-7-2025 10:25:32 P9	Stroking	Mechanics	Low (5N or 3cm/s)	2	7	2	6	4
3-7-2025 10:26:30 P9	Stroking	SMA	High (15N or 10cm/s)	6	3	6	3	7
3-7-2025 10:30:18 P9	Stroking	Mechanics	Low (5N or 3cm/s)	6	4	2	6	6
3-7-2025 10:31:02 P9	Stroking	SMA	High (15N or 10cm/s)	3	3	5	4	5
3-7-2025 10:32:14 P9	Stroking	Mechanics	High (15N or 10cm/s)	1	5	1	6	4
3-7-2025 10:33:18 P9	Stroking	SMA	Low (5N or 3cm/s)	7	4	6	2	7
3-7-2025 10:48:07 P9	Squeeze	Mechanics	High (15N or 10cm/s)	3	3	4	2	5
3-7-2025 10:49:17 P9	Squeeze	SMA	High (15N or 10cm/s)	2	5	6	6	2
3-7-2025 10:50:11 P9	Squeeze	Mechanics	Low (5N or 3cm/s)	5	2	3	3	4
3-7-2025 10:51:20 P9	Squeeze	SMA	Low (5N or 3cm/s)	5	2	6	1	7
3-7-2025 10:55:28 P9	Squeeze	Mechanics	Low (5N or 3cm/s)	6	7	1	2	4
3-7-2025 10:56:42 P9	Squeeze	SMA	Low (5N or 3cm/s)	7	1	7	1	7
3-7-2025 10:57:30 P9	Squeeze	Mechanics	High (15N or 10cm/s)	1	6	2	7	1
3-7-2025 10:58:23 P9	Squeeze	SMA	High (15N or 10cm/s)	2	6	7	6	1
3-7-2025 12:03:06 P10	Squeeze	SMA	Low (5N or 3cm/s)	6	3	6	2	7
3-7-2025 12:04:48 P10	Squeeze	Mechanics	Low (5N or 3cm/s)	3	5	2	3	4
3-7-2025 12:07:30 P10	Squeeze	SMA	High (15N or 10cm/s)	5	4	6	5	3
3-7-2025 12:09:25 P10	Squeeze	Mechanics	High (15N or 10cm/s)	4	4	2	5	3
3-7-2025 12:14:05 P10	Squeeze	SMA	High (15N or 10cm/s)	7	5	6	4	6
3-7-2025 12:15:23 P10	Squeeze	Mechanics	High (15N or 10cm/s)	3	5	2	5	3
3-7-2025 12:18:01 P10	Squeeze	SMA	Low (5N or 3cm/s)	6	1	5	1	6
3-7-2025 12:19:20 P10	Squeeze	Mechanics	Low (5N or 3cm/s)	4	4	3	3	4
3-7-2025 12:44:09 P10	Stroking	SMA	Low (5N or 3cm/s)	3	2	5	2	4
3-7-2025 12:46:12 P10	Stroking	Mechanics	High (15N or 10cm/s)	4	3	5	4	4
3-7-2025 12:48:08 P10	Stroking	SMA	High (15N or 10cm/s)	4	4	5	5	5
3-7-2025 12:49:25 P10	Stroking	Mechanics	Low (5N or 3cm/s)	3	4	2	6	4
3-7-2025 12:51:50 P10	Stroking	SMA	High (15N or 10cm/s)	5	3	5	4	5
3-7-2025 12:52:49 P10	Stroking	Mechanics	High (15N or 10cm/s)	4	4	4	5	4
3-7-2025 12:54:14 P10	Stroking	SMA	Low (5N or 3cm/s)	5	3	5	3	5
3-7-2025 12:55:39 P10	Stroking	Mechanics	Low (5N or 3cm/s)	3	3	3	3	4
3-7-2025 14:00:46 P11	Stroking	SMA	Low (5N or 3cm/s)	4	2	2	3	5
3-7-2025 14:01:51 P11	Stroking	Mechanics	High (15N or 10cm/s)	2	5	5	4	5
3-7-2025 14:02:57 P11	Stroking	SMA	High (15N or 10cm/s)	4	3	3	3	5
3-7-2025 14:04:03 P11	Stroking	Mechanics	Low (5N or 3cm/s)	3	3		4	5
3-7-2025 14:08:08 P11	Stroking	SMA	High (15N or 10cm/s)	3	4	3	3	3
3-7-2025 14:09:05 P11	Stroking	Mechanics	High (15N or 10cm/s)	2	6	3	3	2
3-7-2025 14:10:03 P11	Stroking	SMA	Low (5N or 3cm/s)	5	3	5	3	5
3-7-2025 14:11:36 P11	Stroking	Mechanics	Low (5N or 3cm/s)	5	4	5	5	5
3-7-2025 14:26:46 P11	Squeeze	SMA	Low (5N or 3cm/s)	6	2	6	2	6
3-7-2025 14:27:38 P11	Squeeze	Mechanics	High (15N or 10cm/s)	2	5	5	5	3
3-7-2025 14:28:36 P11	Squeeze	SMA	High (15N or 10cm/s)	4	4	5	5	3
3-7-2025 14:29:52 P11	Squeeze	Mechanics	Low (5N or 3cm/s)	4	3	4	5	4
3-7-2025 14:35:23 P11	Squeeze	Mechanics	High (15N or 10cm/s)	3	4	2	5	4
3-7-2025 14:36:21 P11	Squeeze	SMA	High (15N or 10cm/s)	5	2	6	2	5
3-7-2025 14:37:30 P11	Squeeze	Mechanics	Low (5N or 3cm/s)	4	3	3	3	4
3-7-2025 14:38:25 P11	Squeeze	SMA	Low (5N or 3cm/s)	4	1	5	1	4
3-7-2025 17:17:31 P12	Squeeze	Mechanics	High (15N or 10cm/s)	7	4	1	4	3
3-7-2025 17:18:54 P12	Squeeze	SMA	Low (5N or 3cm/s)	5	1	4	1	6
3-7-2025 17:19:40 P12	Squeeze	Mechanics	Low (5N or 3cm/s)	6	3	1	3	4
3-7-2025 17:20:38 P12	Squeeze	SMA	High (15N or 10cm/s)	3	5	5	4	3
3-7-2025 17:27:02 P12	Squeeze	Mechanics	Low (5N or 3cm/s)	3	4	1	4	4
3-7-2025 17:28:23 P12	Squeeze	SMA	High (15N or 10cm/s)	3	5	5	5	3
3-7-2025 17:29:18 P12	Squeeze	Mechanics	High (15N or 10cm/s)	3	5	1	5	2
3-7-2025 17:30:07 P12	Squeeze	SMA	Low (5N or 3cm/s)	6	2	6	2	5
3-7-2025 17:53:14 P12	Stroking	Mechanics	Low (5N or 3cm/s)	3	2	1	4	5
3-7-2025 17:54:18 P12	Stroking	SMA	Low (5N or 3cm/s)	6	1	5	3	6
3-7-2025 17:55:14 P12	Stroking	Mechanics	High (15N or 10cm/s)	3	4		3	4
3-7-2025 17:56:10 P12	Stroking	SMA	High (15N or 10cm/s)	6	2	5	4	5
3-7-2025 17:58:04 P12	Stroking	SMA	Low (5N or 3cm/s)	7	3	5	5	6
3-7-2025 17:58:57 P12	Stroking	Mechanics	High (15N or 10cm/s)	2	3	1	5	3
3-7-2025 17:59:47 P12	Stroking	SMA	High (15N or 10cm/s)	7	5	7	6	7
3-7-2025 18:00:33 P12	Stroking	Mechanics	Low (5N or 3cm/s)	6	4	3	5	6
3-10-2025 10:14:33 P13	Stroking	SMA	Low (5N or 3cm/s)	5	2	5	4	6
3-10-2025 10:16:05 P13	Stroking	Mechanics	Low (5N or 3cm/s)	4	3	4	4	5
3-10-2025 10:17:11 P13	Stroking	SMA	High (15N or 10cm/s)	4	1	5	5	4
3-10-2025 10:18:21 P13	Stroking	Mechanics	High (15N or 10cm/s)	4	4	3	5	3
3-10-2025 10:26:07 P13	Stroking	Mechanics	High (15N or 10cm/s)	4	3	3	4	4
3-10-2025 10:27:08 P13	Stroking	SMA	Low (5N or 3cm/s)	6	4	5	4	6
3-10-2025 10:28:15 P13	Stroking	Mechanics	Low (5N or 3cm/s)	5	3	5	3	5
3-10-2025 10:29:05 P13	Stroking	SMA	High (15N or 10cm/s)	5	5	5	6	3
3-10-2025 10:47:02 P13	Squeeze	Mechanics	Low (5N or 3cm/s)	3	6	3	5	2
3-10-2025 10:48:19 P13	Squeeze	SMA	High (15N or 10cm/s)	5	4	5	4	5
3-10-2025 10:49:08 P13	Squeeze	Mechanics	High (15N or 10cm/s)	3	5	2	5	3
3-10-2025 10:50:06 P13	Squeeze	SMA	Low (5N or 3cm/s)	4	2	4	1	5
3-10-2025 10:54:56 P13	Squeeze	SMA	High (15N or 10cm/s)	5	4	5	4	5
3-10-2025 10:55:40 P13	Squeeze	Mechanics	Low (5N or 3cm/s)	2	5	2	5	2
3-10-2025 10:56:30 P13	Squeeze	SMA	Low (5N or 3cm/s)	4	1	4	1	4
3-10-2025 10:57:28 P13	Squeeze	Mechanics	High (15N or 10cm/s)	2	5	3	5	3
3-10-2025 12:00:37 P14	Squeeze	Mechanics	High (15N or 10cm/s)	4	5	1	5	4
3-10-2025 12:01:48 P14	Squeeze	SMA	High (15N or 10cm/s)	5	5	6	5	6
3-10-2025 12:02:39 P14	Squeeze	Mechanics	Low (5N or 3cm/s)	4	4	1	4	4
3-10-2025 12:03:41 P14	Squeeze	SMA	Low (5N or 3cm/s)	5	3	6	3	6
3-10-2025 12:08:48 P14	Squeeze	SMA	High (15N or 10cm/s)	6	3	6	3	6
3-10-2025 12:09:29 P14	Squeeze	Mechanics	Low (5N or 3cm/s)	3	5	2	6	2
3-10-2025 12:10:11 P14	Squeeze	SMA	Low (5N or 3cm/s)	6	3	6	3	6
3-10-2025 12:10:50 P14	Squeeze	Mechanics	High (15N or 10cm/s)	4	6	3	6	3
3-10-2025 12:23:59 P14	Stroking	SMA	High (15N or 10cm/s)	4	6	4	3	5

3-10-2025 12:24:48 P14	Stroking	Mechanics	High (15N or 10cm/s)	5	3	3	4	4
3-10-2025 12:25:39 P14	Stroking	SMA	Low (5N or 3cm/s)	6	4	4	3	6
3-10-2025 12:26:37 P14	Stroking	Mechanics	Low (5N or 3cm/s)	5	4	3	3	5
3-10-2025 12:29:26 P14	Stroking	Mechanics	High (15N or 10cm/s)	6	3	5	4	6
3-10-2025 12:29:57 P14	Stroking	SMA	Low (5N or 3cm/s)	6	3	5	4	6
3-10-2025 12:30:45 P14	Stroking	Mechanics	Low (5N or 3cm/s)	6	3	5	4	6
3-10-2025 12:31:19 P14	Stroking	SMA	High (15N or 10cm/s)	5	3	6	3	6
3-10-2025 13:43:53 P15	Stroking	SMA	Low (5N or 3cm/s)	5	2	6	5	5
3-10-2025 13:45:47 P15	Stroking	Mechanics	High (15N or 10cm/s)	3	4	2	5	4
3-10-2025 13:47:05 P15	Stroking	SMA	High (15N or 10cm/s)	4	2	5	6	5
3-10-2025 13:47:55 P15	Stroking	Mechanics	Low (5N or 3cm/s)	3	5	2	2	4
3-10-2025 13:50:47 P15	Stroking	SMA	High (15N or 10cm/s)	6	3	3	3	5
3-10-2025 13:51:42 P15	Stroking	Mechanics	High (15N or 10cm/s)	4	3	4	4	4
3-10-2025 13:52:56 P15	Stroking	SMA	Low (5N or 3cm/s)	5	3	4	4	5
3-10-2025 13:53:54 P15	Stroking	Mechanics	Low (5N or 3cm/s)	4	3	2	3	4
3-10-2025 14:12:03 P15	Squeeze	SMA	Low (5N or 3cm/s)	5	4	6	4	6
3-10-2025 14:13:18 P15	Squeeze	Mechanics	Low (5N or 3cm/s)	3	3	1	2	3
3-10-2025 14:14:28 P15	Squeeze	SMA	High (15N or 10cm/s)	5	5	6	5	5
3-10-2025 14:15:21 P15	Squeeze	Mechanics	High (15N or 10cm/s)	3	4	1	4	4
3-10-2025 14:24:13 P15	Squeeze	SMA	Low (5N or 3cm/s)	4	2	5	2	6
3-10-2025 14:25:35 P15	Squeeze	Mechanics	High (15N or 10cm/s)	2	6	1	6	2
3-10-2025 14:26:54 P15	Squeeze	SMA	High (15N or 10cm/s)	6	5	7	5	6
3-10-2025 14:27:38 P15	Squeeze	Mechanics	Low (5N or 3cm/s)	3	5	1	4	3
3-10-2025 15:32:19 P16	Squeeze	Mechanics	Low (5N or 3cm/s)	4	5	5	3	5
3-10-2025 15:33:59 P16	Squeeze	SMA	Low (5N or 3cm/s)	6	3	6	2	7
3-10-2025 15:34:57 P16	Squeeze	Mechanics	High (15N or 10cm/s)	6	6	2	5	4
3-10-2025 15:36:12 P16	Squeeze	SMA	High (15N or 10cm/s)	7	5	6	3	6
3-10-2025 15:42:08 P16	Squeeze	Mechanics	High (15N or 10cm/s)	3	6	2	7	2
3-10-2025 15:43:16 P16	Squeeze	SMA	Low (5N or 3cm/s)	7	1	6	1	7
3-10-2025 15:44:15 P16	Squeeze	Mechanics	Low (5N or 3cm/s)	6	5	3	6	4
3-10-2025 15:45:17 P16	Squeeze	SMA	High (15N or 10cm/s)	6	3	5	4	6
3-10-2025 15:57:32 P16	Stroking	Mechanics	High (15N or 10cm/s)	3	4	3	6	5
3-10-2025 15:58:49 P16	Stroking	SMA	Low (5N or 3cm/s)	6	4	5	3	6
3-10-2025 16:01:04 P16	Stroking	Mechanics	Low (5N or 3cm/s)	5	2	2	3	7
3-10-2025 16:01:56 P16	Stroking	SMA	High (15N or 10cm/s)	6	3	6	2	6
3-10-2025 16:04:14 P16	Stroking	SMA	Low (5N or 3cm/s)	6	3	6	2	7
3-10-2025 16:04:59 P16	Stroking	Mechanics	Low (5N or 3cm/s)	2	5	2	6	4
3-10-2025 16:05:55 P16	Stroking	SMA	High (15N or 10cm/s)	5	5	6	3	7
3-10-2025 16:06:41 P16	Stroking	Mechanics	High (15N or 10cm/s)	3	6	2	5	3
3-11-2025 10:10:21 P17	Stroking	SMA	Low (5N or 3cm/s)	5	4	6	2	5
3-11-2025 10:11:29 P17	Stroking	Mechanics	High (15N or 10cm/s)	6	6	5	3	5
3-11-2025 10:12:24 P17	Stroking	SMA	High (15N or 10cm/s)	5	4	5	2	5
3-11-2025 10:13:29 P17	Stroking	Mechanics	Low (5N or 3cm/s)	4	4	6	2	4
3-11-2025 10:15:34 P17	Stroking	Mechanics	Low (5N or 3cm/s)	5	4	6	3	6
3-11-2025 10:16:30 P17	Stroking	SMA	High (15N or 10cm/s)	4	2	5	3	4
3-11-2025 10:17:22 P17	Stroking	Mechanics	High (15N or 10cm/s)	4	5	5	4	3
3-11-2025 10:18:11 P17	Stroking	SMA	Low (5N or 3cm/s)	5	3	5	3	5
3-11-2025 10:32:21 P17	Squeeze	Mechanics	High (15N or 10cm/s)	5	6	7	5	5
3-11-2025 10:33:29 P17	Squeeze	SMA	High (15N or 10cm/s)	5	6	6	5	3
3-11-2025 10:34:18 P17	Squeeze	Mechanics	Low (5N or 3cm/s)	5	6	6	5	5
3-11-2025 10:35:05 P17	Squeeze	SMA	Low (5N or 3cm/s)	5	5	5	4	4
3-11-2025 10:40:49 P17	Squeeze	Mechanics	High (15N or 10cm/s)	6	6	6	5	5
3-11-2025 10:42:01 P17	Squeeze	SMA	Low (5N or 3cm/s)	4	3	4	2	4
3-11-2025 10:42:51 P17	Squeeze	Mechanics	Low (5N or 3cm/s)	5	6	5	5	5
3-11-2025 10:43:48 P17	Squeeze	SMA	High (15N or 10cm/s)	5	3	4	3	4
3-11-2025 12:01:04 P18	Squeeze	Mechanics	High (15N or 10cm/s)	3	5	2	6	2
3-11-2025 12:03:16 P18	Squeeze	SMA	High (15N or 10cm/s)	4	2	3	5	4
3-11-2025 12:04:58 P18	Squeeze	Mechanics	Low (5N or 3cm/s)	4	2	5	3	6
3-11-2025 12:06:11 P18	Squeeze	SMA	Low (5N or 3cm/s)	4	2	3	1	5
3-11-2025 12:11:09 P18	Squeeze	SMA	Low (5N or 3cm/s)	5	1	5	1	7
3-11-2025 12:12:02 P18	Squeeze	Mechanics	Low (5N or 3cm/s)	3	5	2	5	3
3-11-2025 12:13:30 P18	Squeeze	SMA	High (15N or 10cm/s)	2	6	1	6	3
3-11-2025 12:14:25 P18	Squeeze	Mechanics	High (15N or 10cm/s)	3	5	3	5	2
3-11-2025 12:34:23 P18	Stroking	SMA	High (15N or 10cm/s)	6	2	5	2	6
3-11-2025 12:35:51 P18	Stroking	Mechanics	High (15N or 10cm/s)	3	4	3	5	5
3-11-2025 12:37:17 P18	Stroking	SMA	Low (5N or 3cm/s)	5	3	5	2	6
3-11-2025 12:38:48 P18	Stroking	Mechanics	Low (5N or 3cm/s)	2	3	5	6	5
3-11-2025 12:41:09 P18	Stroking	Mechanics	High (15N or 10cm/s)	4	5	3	5	5
3-11-2025 12:42:31 P18	Stroking	SMA	High (15N or 10cm/s)	6	2	4	6	5
3-11-2025 12:43:38 P18	Stroking	Mechanics	Low (5N or 3cm/s)	5	2	1	2	5
3-11-2025 12:44:49 P18	Stroking	SMA	Low (5N or 3cm/s)	6	2	5	6	6
3-11-2025 13:47:40 P19	Stroking	Mechanics	Low (5N or 3cm/s)	6	2	3	5	5
3-11-2025 13:48:50 P19	Stroking	SMA	High (15N or 10cm/s)	4	4	4	6	3
3-11-2025 13:50:23 P19	Stroking	Mechanics	High (15N or 10cm/s)	3	5	2	4	3
3-11-2025 13:51:27 P19	Stroking	SMA	Low (5N or 3cm/s)	4	5	3	5	5
3-11-2025 13:54:26 P19	Stroking	SMA	High (15N or 10cm/s)	5	2	3	5	4
3-11-2025 13:55:19 P19	Stroking	Mechanics	Low (5N or 3cm/s)	5	5	5	5	6
3-11-2025 13:56:14 P19	Stroking	SMA	Low (5N or 3cm/s)	5	2	4	4	4
3-11-2025 13:58:05 P19	Stroking	Mechanics	High (15N or 10cm/s)	6	7	2	5	6
3-11-2025 14:22:08 P19	Squeeze	SMA	Low (5N or 3cm/s)	3	2	5	2	5
3-11-2025 14:23:29 P19	Squeeze	Mechanics	High (15N or 10cm/s)	3	3	1	2	4
3-11-2025 14:24:33 P19	Squeeze	SMA	High (15N or 10cm/s)	5	3	5	4	5
3-11-2025 14:25:30 P19	Squeeze	Mechanics	Low (5N or 3cm/s)	3	1	1	2	2
3-11-2025 14:35:07 P19	Squeeze	SMA	High (15N or 10cm/s)	4	2	5	2	4
3-11-2025 14:36:01 P19	Squeeze	Mechanics	High (15N or 10cm/s)	5	5	2	5	3
3-11-2025 14:37:27 P19	Squeeze	SMA	Low (5N or 3cm/s)	2	1	6	1	4
3-11-2025 14:38:10 P19	Squeeze	Mechanics	Low (5N or 3cm/s)	6	6	1	6	6
3-11-2025 15:27:50 P20	Squeeze	SMA	High (15N or 10cm/s)	3	2	3	4	7
3-11-2025 15:29:47 P20	Squeeze	Mechanics	High (15N or 10cm/s)	5	4	5	5	4
3-11-2025 15:31:26 P20	Squeeze	SMA	Low (5N or 3cm/s)	1	6	3	1	3
3-11-2025 15:32:17 P20	Squeeze	Mechanics	Low (5N or 3cm/s)	4	1	6	1	4
3-11-2025 15:36:41 P20	Squeeze	Mechanics	Low (5N or 3cm/s)	4	3	6	2	5
3-11-2025 15:38:14 P20	Squeeze	SMA	High (15N or 10cm/s)	3	3	3	4	4
3-11-2025 15:39:04 P20	Squeeze	Mechanics	High (15N or 10cm/s)	4	3	5	5	3
3-11-2025 15:40:00 P20	Squeeze	SMA	Low (5N or 3cm/s)	4	1	2	1	4
3-11-2025 16:00:35 P20	Stroking	Mechanics	Low (5N or 3cm/s)	3	2	1	6	4
3-11-2025 16:01:43 P20	Stroking	SMA	Low (5N or 3cm/s)	5	2	6	3	6
3-11-2025 16:02:46 P20	Stroking	Mechanics	High (15N or 10cm/s)	4	5	1	7	4
3-11-2025 16:04:29 P20	Stroking	SMA	High (15N or 10cm/s)	3	3	5	2	4
3-11-2025 16:09:00 P20	Stroking	Mechanics	High (15N or 10cm/s)	3	2	1	6	4
3-11-2025 16:09:50 P20	Stroking	SMA	High (15N or 10cm/s)	6	1	4	2	6
3-11-2025 16:10:40 P20	Stroking	Mechanics	Low (5N or 3cm/s)	5	1	3	5	5
3-11-2025 16:11:25 P20	Stroking	SMA	Low (5N or 3cm/s)	5	2	5	2	6
3-12-2025 15:37:37 P21	Stroking	SMA	Low (5N or 3cm/s)	6	3	5	4	6
3-12-2025 15:39:28 P21	Stroking	Mechanics	High (15N or 10cm/s)	4	5	3	5	4
3-12-2025 15:41:08 P21	Stroking	SMA	High (15N or 10cm/s)	5	5	4	5	4
3-12-2025 15:42:34 P21	Stroking	Mechanics	Low (5N or 3cm/s)	5	6	3	3	4
3-12-2025 15:47:02 P21	Stroking	Mechanics	High (15N or 10cm/s)	3	6	2	6	3
3-12-2025 15:48:10 P21	Stroking	SMA	High (15N or 10cm/s)	6	3	5	3	6

3-12-2025 15:49:42 P21	Stroking	Mechanics	Low (5N or 3cm/s)	3	5	2	3	3
3-12-2025 15:51:19 P21	Stroking	SMA	Low (5N or 3cm/s)	6	4	6	3	6
3-12-2025 16:12:16 P21	Squeeze	Mechanics	High (15N or 10cm/s)	5	5	3	5	5
3-12-2025 16:13:29 P21	Squeeze	SMA	High (15N or 10cm/s)	6	6	6	6	6
3-12-2025 16:14:47 P21	Squeeze	Mechanics	Low (5N or 3cm/s)	5	5	3	5	5
3-12-2025 16:17:05 P21	Squeeze	SMA	Low (5N or 3cm/s)	7	5	6	5	6
3-12-2025 16:25:02 P21	Squeeze	SMA	Low (5N or 3cm/s)	5	3	6	3	5
3-12-2025 16:29:10 P21	Squeeze	Mechanics	High (15N or 10cm/s)	3	6	3	6	4
3-12-2025 16:30:16 P21	Squeeze	SMA	High (15N or 10cm/s)	6	5	6	6	6
3-12-2025 16:32:10 P21	Squeeze	Mechanics	Low (5N or 3cm/s)	6	4	2	4	5
3-13-2025 11:59:47 P22	Squeeze	Mechanics	Low (5N or 3cm/s)	3	5	2	5	2
3-13-2025 12:01:05 P22	Squeeze	SMA	High (15N or 10cm/s)	5	2	5	2	5
3-13-2025 12:02:25 P22	Squeeze	Mechanics	High (15N or 10cm/s)	2	4	2	3	3
3-13-2025 12:03:23 P22	Squeeze	SMA	Low (5N or 3cm/s)	3	1	4	1	4
3-13-2025 12:08:49 P22	Squeeze	Mechanics	Low (5N or 3cm/s)	1	6	1	7	1
3-13-2025 12:10:13 P22	Squeeze	SMA	Low (5N or 3cm/s)	3	1	5	1	4
3-13-2025 12:11:05 P22	Squeeze	Mechanics	High (15N or 10cm/s)	3	5	2	6	1
3-13-2025 12:12:32 P22	Squeeze	SMA	High (15N or 10cm/s)	2	3	5	2	4
3-13-2025 12:26:20 P22	Stroking	Mechanics	High (15N or 10cm/s)	2	5	2	4	3
3-13-2025 12:27:08 P22	Stroking	SMA	High (15N or 10cm/s)	3	3	2	6	3
3-13-2025 12:28:02 P22	Stroking	Mechanics	Low (5N or 3cm/s)	2	2	2	3	3
3-13-2025 12:28:51 P22	Stroking	SMA	Low (5N or 3cm/s)	2	3	2	3	4
3-13-2025 12:31:37 P22	Stroking	Mechanics	High (15N or 10cm/s)	3	4	1	4	4
3-13-2025 12:32:25 P22	Stroking	SMA	Low (5N or 3cm/s)	1	5	2	6	3
3-13-2025 12:33:12 P22	Stroking	Mechanics	Low (5N or 3cm/s)	1	5	1	2	4
3-13-2025 12:34:18 P22	Stroking	SMA	High (15N or 10cm/s)	3	3	4	6	4

Results

Appendix H - statistical analysis results

Correlation

Squeeze data - correlations

Pearson's Correlations

Variable		Force_Mechanical	Human-likeness_Mechanical	Intensity_Mechanical	Pleasantness_Mechanical	Tone_Mechanical	Force_SMA	Human-likeness_SMA	Intensity_SMA	Pleasantness_SMA	Tone_SMA
1. Force_Mechanical	Pearson's r	—									
	p-value	—									
2. Human-likeness_Mechanical	Pearson's r	0.300	—								
	p-value	0.174	—								
3. Intensity_Mechanical	Pearson's r	0.760	0.134	—							
	p-value	< .001	0.551	—							
4. Pleasantness_Mechanical	Pearson's r	0.126	0.460	0.104	—						
	p-value	0.577	0.031	0.645	—						
5. Tone_Mechanical	Pearson's r	0.179	0.580	0.081	0.829	—					
	p-value	0.424	0.005	0.721	< .001	—					
6. Force_SMA	Pearson's r	0.376	0.334	0.310	0.487	0.645	—				
	p-value	0.084	0.129	0.161	0.021	0.001	—				
7. Human-likeness_SMA	Pearson's r	-0.059	-0.567	0.232	-0.039	-0.016	0.128	—			
	p-value	0.793	0.006	0.298	0.863	0.942	0.569	—			
8. Intensity_SMA	Pearson's r	0.372	0.288	0.404	0.570	0.679	0.909	0.175	—		
	p-value	0.089	0.194	0.062	0.006	< .001	< .001	0.437	—		
9. Pleasantness_SMA	Pearson's r	0.346	-0.067	0.507	0.226	0.227	0.359	0.546	0.402	—	
	p-value	0.114	0.768	0.016	0.311	0.310	0.101	0.009	0.063	—	
10. Tone_SMA	Pearson's r	0.083	-0.243	0.095	-0.147	-0.131	-0.047	0.344	-0.090	0.641	—
	p-value	0.713	0.276	0.673	0.515	0.561	0.835	0.117	0.691	0.001	—

Squeeze - Humanlikeness

Results

Repeated Measures ANOVA - Humanlike

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		69.136	1	69.136	12.266	0.002
Residuals		118.364	21	5.636		
Actual force		0.409	1	0.409	0.711	0.409
Residuals		12.091	21	0.576		
Actuation method	Actual force	2.227	1	2.227	4.059	0.057
Residuals		11.523	21	0.549		

Note. Type III Sum of Squares

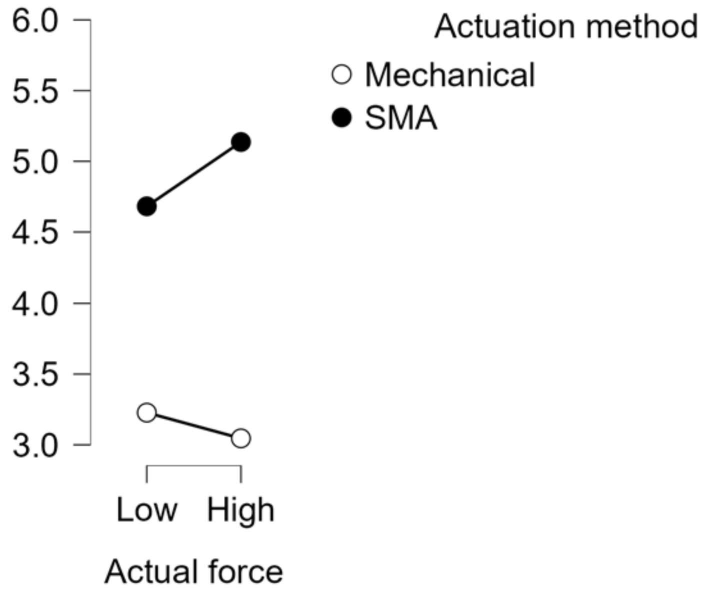
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	39.705	21	1.891		

Note. Type III Sum of Squares

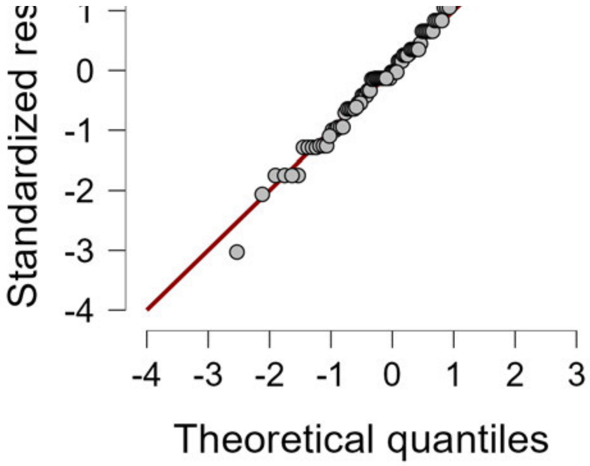
Descriptives

Descriptives plots



Assumption Checks

Q-Q Plot



Paired Samples T-Test - Humanlike

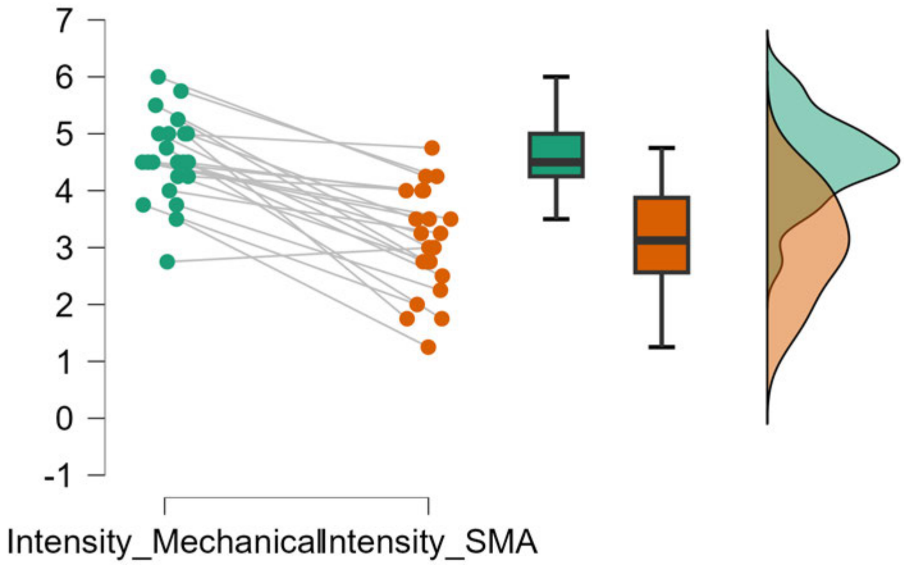
Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p
Intensity_Mechanical	-	Intensity_SMA	Student	7.461		21	< .001
			Wilcoxon	251.000	4.042		< .001
Intensity_Mechanical_High	-	Intensity_SMA_High	Student	2.812		21	0.010
			Wilcoxon	130.500	2.556		0.010
Intensity_Mechanical_Low	-	Intensity_SMA_Low	Student	7.972		21	< .001
			Wilcoxon	248.000	3.945		< .001

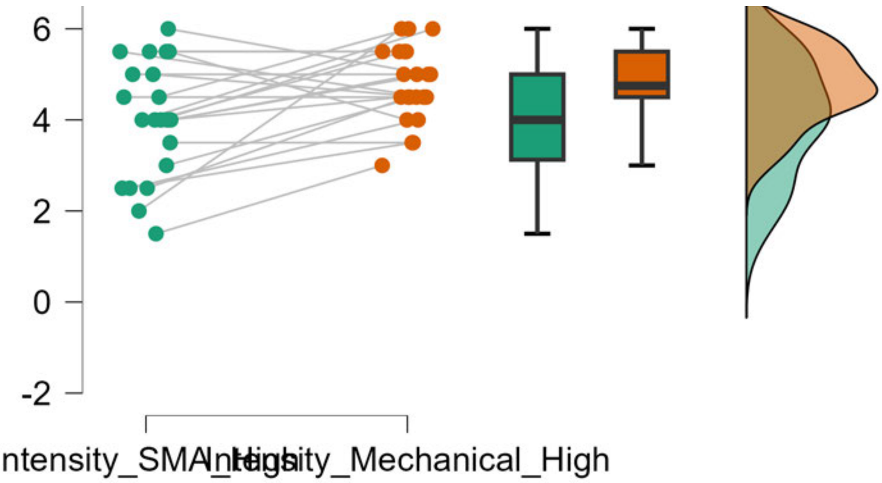
Descriptives

Raincloud Plots

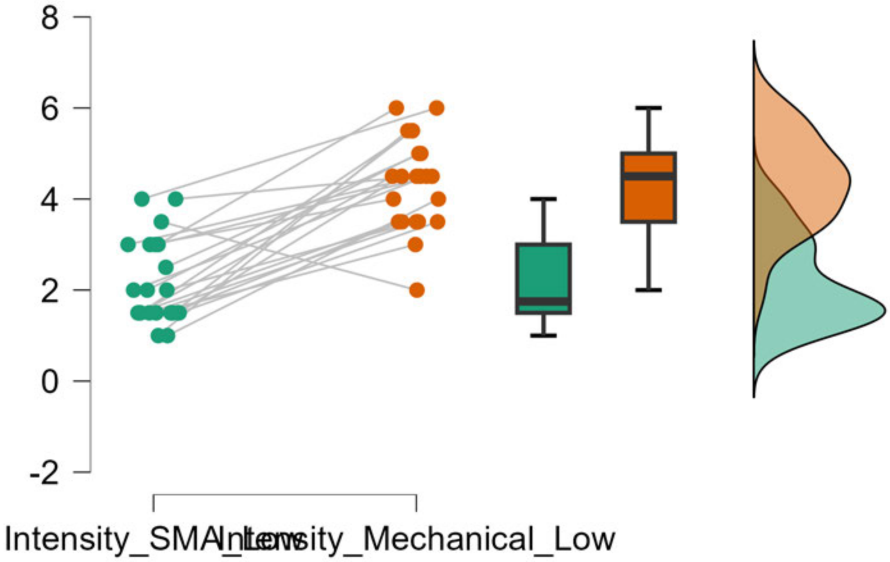
Intensity_Mechanical - Intensity_SMA



Intensity_Mechanical_High - Intensity_SMA_High



Intensity_Mechanical_Low - Intensity_SMA_Low



Results

Squeeze - Intensity

Repeated Measures ANOVA - Intensity

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		48.011	1	48.011	55.662	< .001
Residuals		18.114	21	0.863		
Actual force		28.409	1	28.409	47.858	< .001
Residuals		12.466	21	0.594		
Actuation method	Actual force	11.636	1	11.636	15.284	< .001
Residuals		15.989	21	0.761		

Note. Type III Sum of Squares

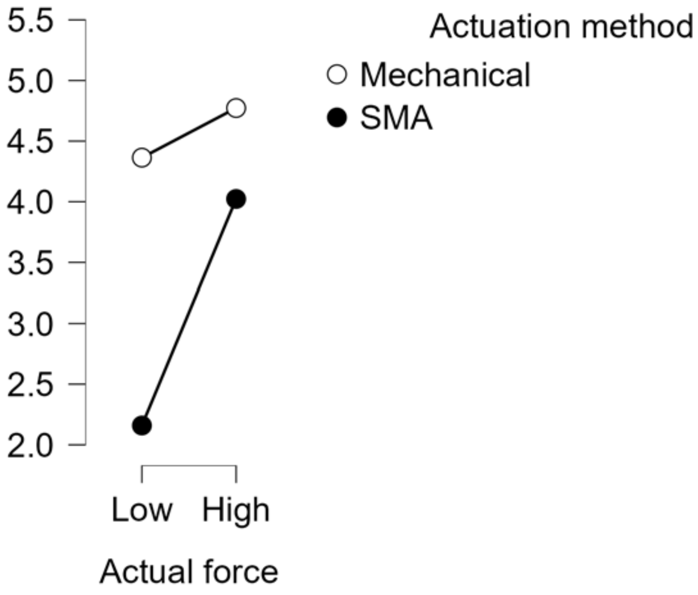
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	41.818	21	1.991		

Note. Type III Sum of Squares

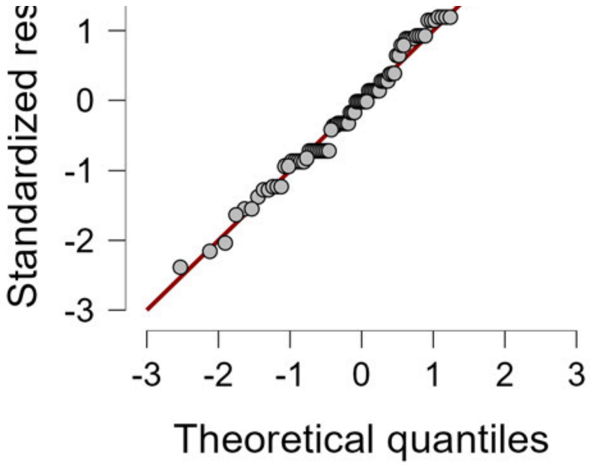
Descriptives

Descriptives plots



Assumption Checks

Q-Q Plot



Paired Samples T-Test - Intensity

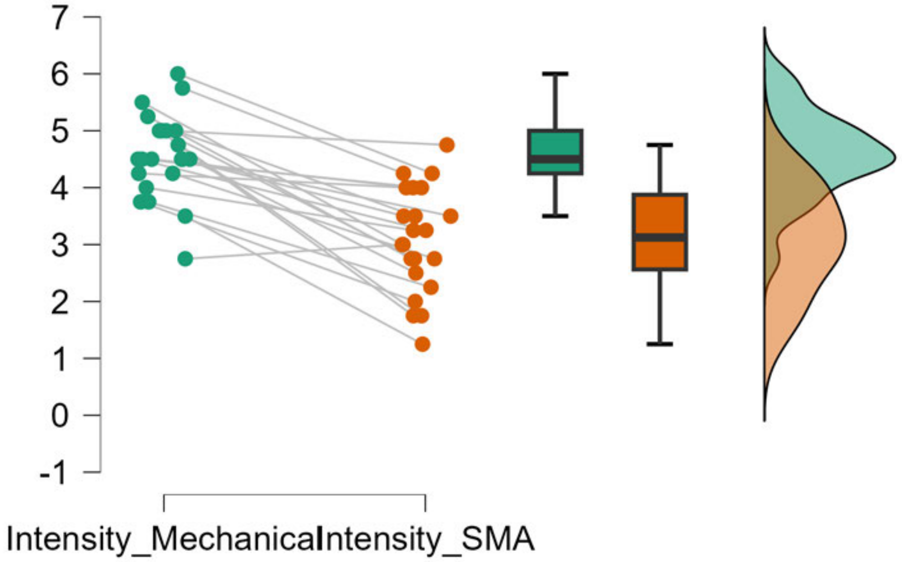
Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p
Intensity_Mechanical	-	Intensity_SMA	Student	7.461		21	< .001
			Wilcoxon	251.000	4.042		< .001
Intensity_Mechanical_High	-	Intensity_SMA_High	Student	2.812		21	0.010
			Wilcoxon	130.500	2.556		0.010
Intensity_Mechanical_Low	-	Intensity_SMA_Low	Student	7.972		21	< .001
			Wilcoxon	248.000	3.945		< .001
Intensity_Mechanical_High	-	Intensity_Mechanical_Low	Student	1.748		21	0.095
			Wilcoxon	126.000	1.764		0.077
Intensity_SMA_High	-	Intensity_SMA_Low	Student	7.127		21	< .001
			Wilcoxon	247.500	3.928		< .001

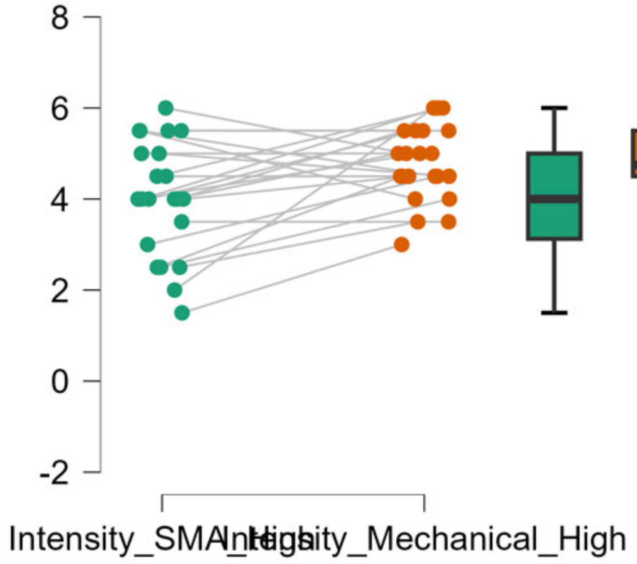
Descriptives

Raincloud Plots

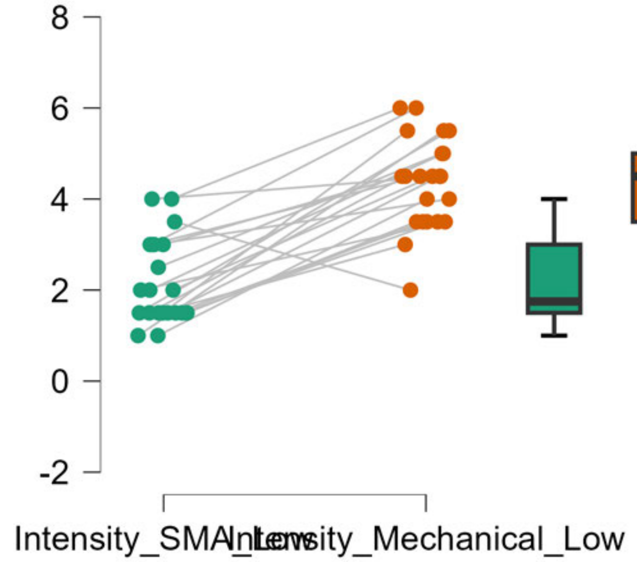
Intensity_Mechanical - Intensity_SMA



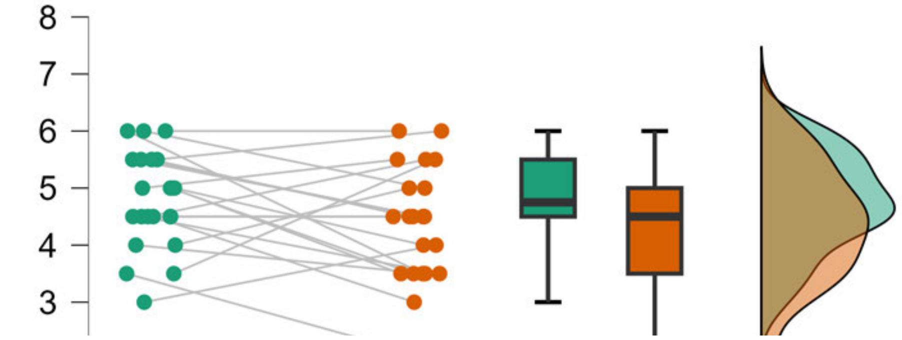
Intensity_Mechanical_High - Intensity_SMA_High



Intensity_Mechanical_Low - Intensity_SMA_Low

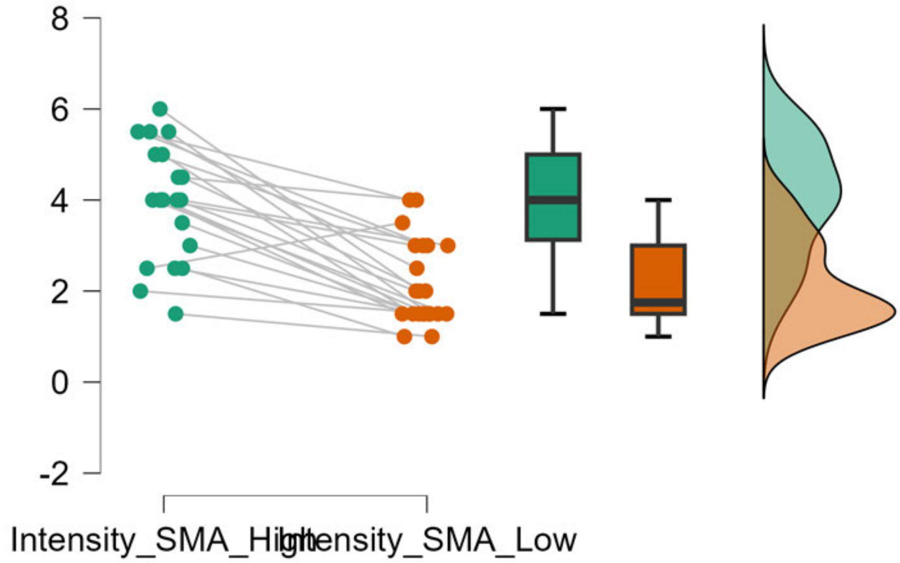


Intensity_Mechanical_High - Intensity_Mechanical_Low



ntensity_Mechanical_High Intensity_Mechanical_Low

Intensity_SMA_High - Intensity_SMA_Low



Results Squeeze - Perceived force

Repeated Measures ANOVA - Perceived force

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		45.821	1	45.821	46.958	< .001
Residuals		20.491	21	0.976		
Actual force		47.276	1	47.276	42.633	< .001
Residuals		23.287	21	1.109		
Actuation method	Actual force	24.571	1	24.571	32.267	< .001
Residuals		15.991	21	0.761		

Note. Type III Sum of Squares

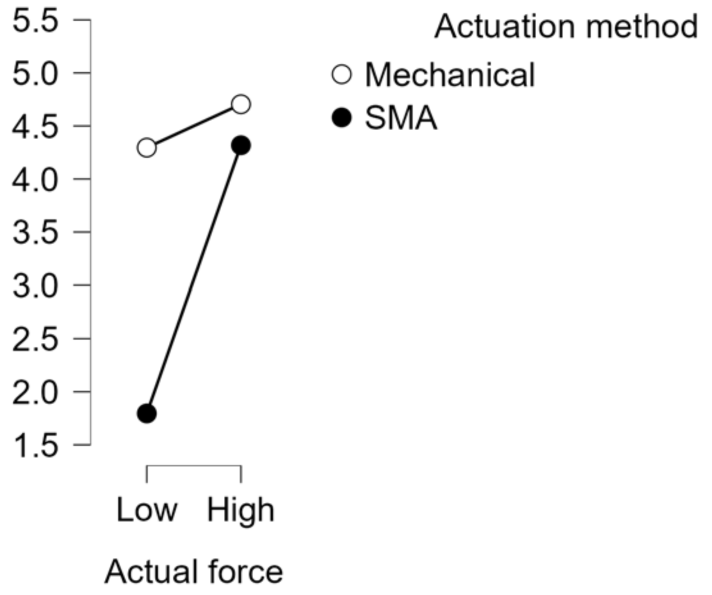
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	43.991	21	2.095		

Note. Type III Sum of Squares

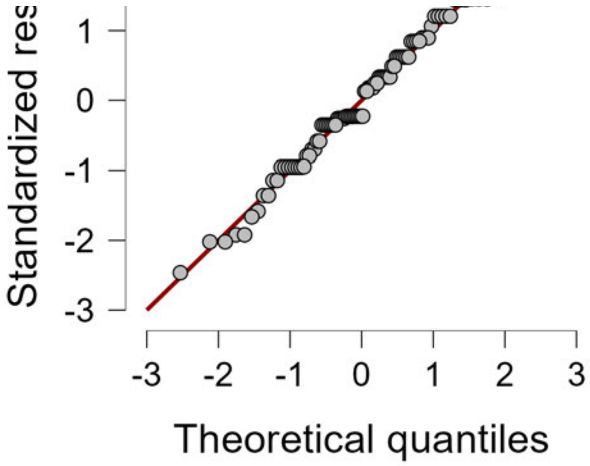
Descriptives

Descriptives plots



Assumption Checks

Q-Q Plot



Paired Samples T-Test - Perceived force

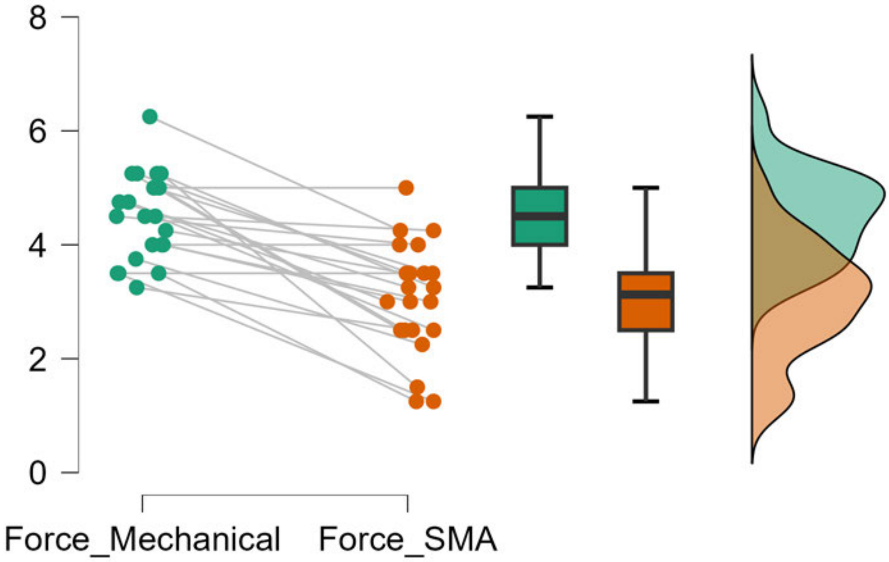
Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p
Force_Mechanical	-	Force_SMA	Student	6.853		21	< .001
			Wilcoxon	190.000	3.823		< .001
Force_Mechanical_High	-	Force_SMA_High	Student	1.290		21	0.211
			Wilcoxon	113.000	1.198		0.238
Force_Mechanical_Low	-	Force_SMA_Low	Student	9.574		21	< .001
			Wilcoxon	231.000	4.015		< .001
Force_Mechanical_High	-	Force_Mechanical_Low	Student	1.344		21	0.193
			Wilcoxon	129.500	1.388		0.169
Force_SMA_High	-	Force_SMA_Low	Student	9.070		21	< .001
			Wilcoxon	253.000	4.107		< .001

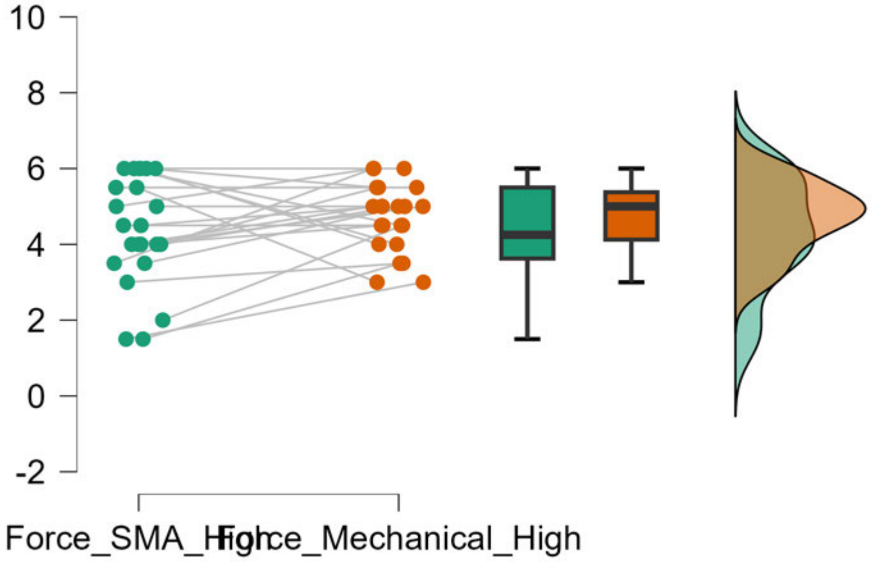
Descriptives

Raincloud Plots

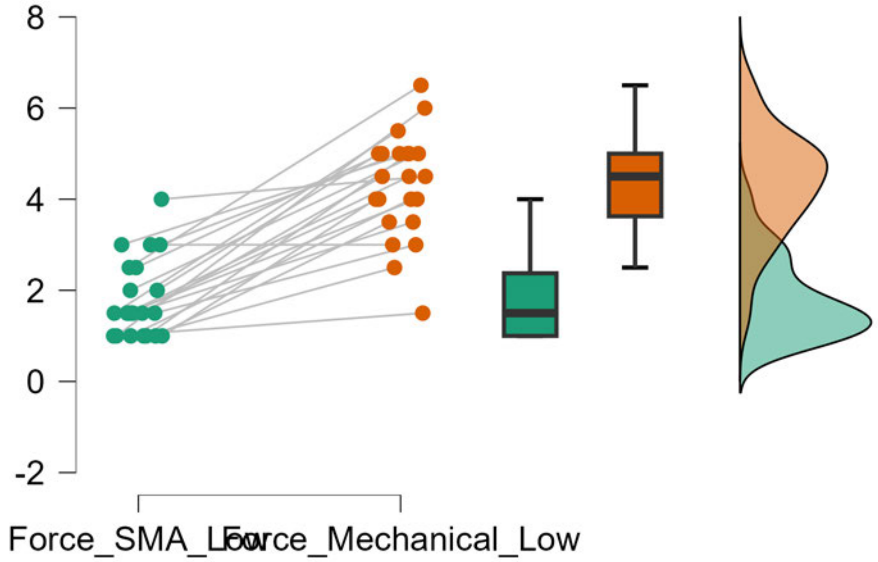
Force_Mechanical - Force_SMA



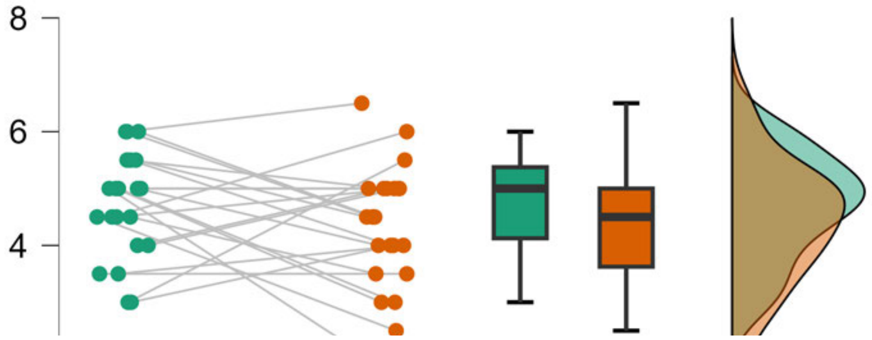
Force_Mechanical_High - Force_SMA_High



Force_Mechanical_Low - Force_SMA_Low

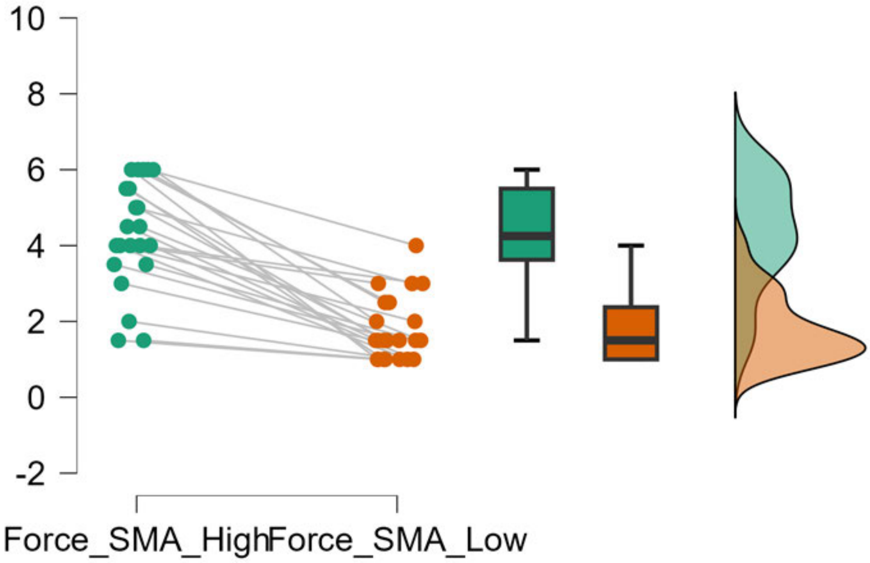


Force_Mechanical_High - Force_Mechanical_Low



Force_Mechanical_HighForce_Mechanical_Low

Force_SMA_High - Force_SMA_Low



Results

Squeeze - Pleasantness

Repeated Measures ANOVA - Pleasantness

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		17.284	1	17.284	13.037	0.002
Residuals		27.841	21	1.326		
Actual force		1.375	1	1.375	1.298	0.267
Residuals		22.250	21	1.060		
Actuation method	Actual force	0.727	1	0.727	1.543	0.228
Residuals		9.898	21	0.471		

Note. Type III Sum of Squares

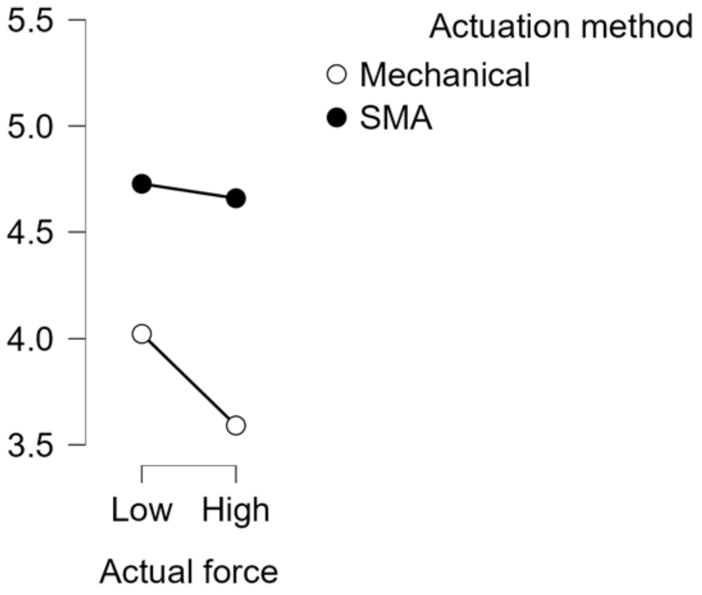
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	44.125	21	2.101		

Note. Type III Sum of Squares

Descriptives

Descriptives plots



Paired Samples T-Test - Pleasantness

Paired Samples T-Test

Measure 1	Measure 2	t	df	p

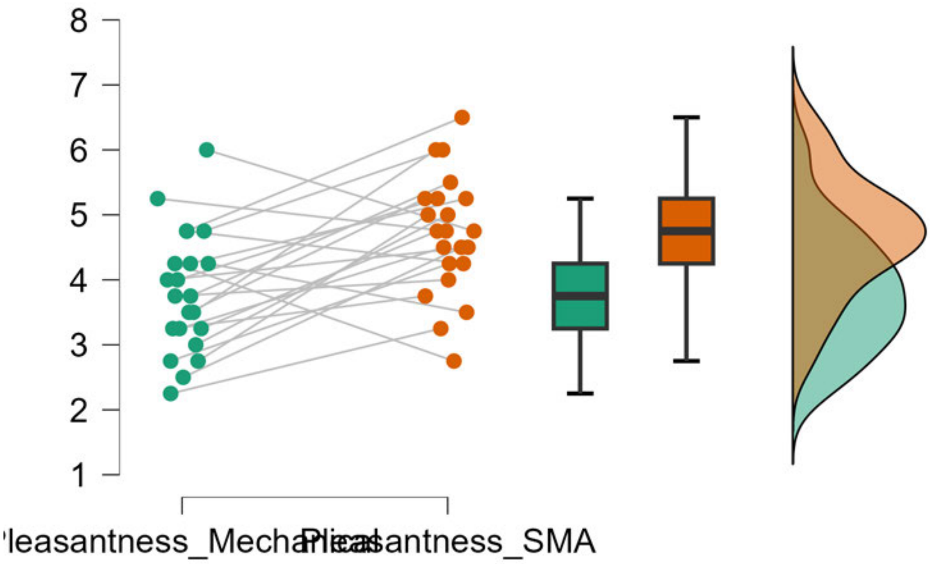
Pleasantness_Mechanical	-	Pleasantness_SMA	-3.611	21	0.002
Pleasantness_Mechanical_High	-	Pleasantness_SMA_High	-3.362	21	0.003
Pleasantness_Mechanical_Low	-	Pleasantness_SMA_Low	-2.820	21	0.010

Note. Student's t-test.

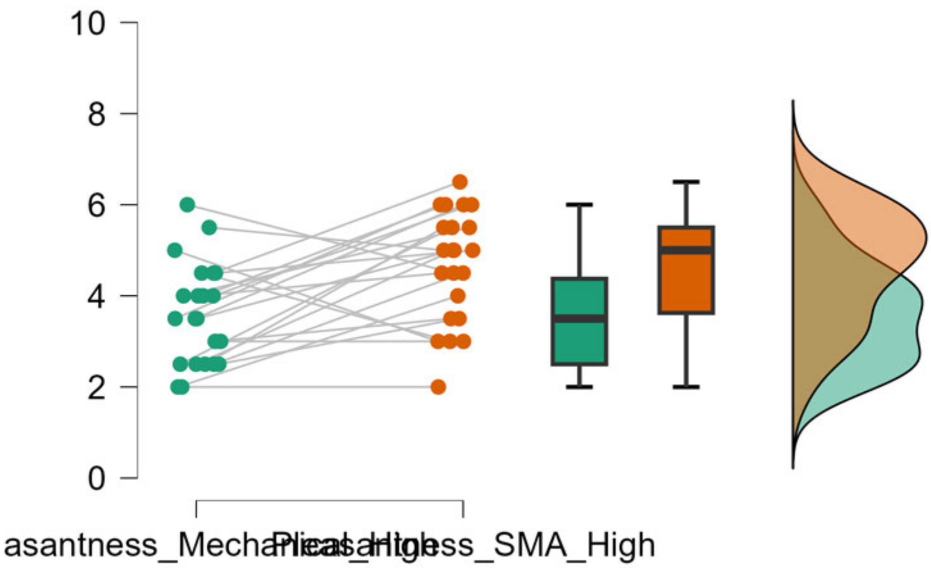
Descriptives

Raincloud Plots

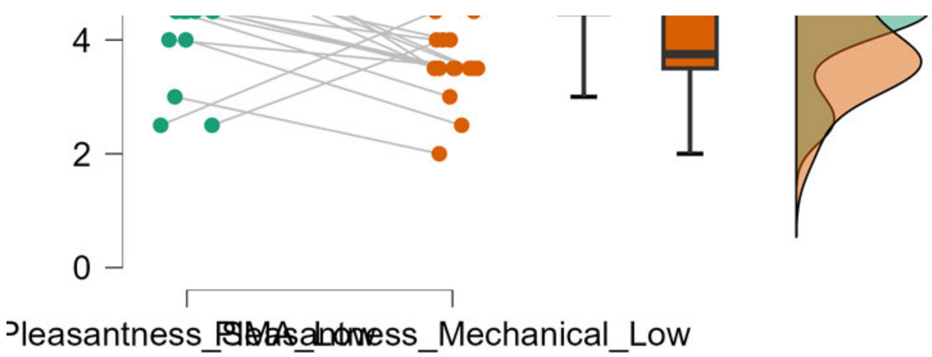
Pleasantness_Mechanical - Pleasantness_SMA



Pleasantness_Mechanical_High - Pleasantness_SMA_High



Pleasantness_Mechanical_Low - Pleasantness_SMA_Low


4
2
0
Pleasantness_PMA_Low
Pleasantness_Mechanical_Low

Results

Squeeze - Friendliness

Repeated Measures ANOVA - Tone

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		48.753	1	48.753	34.345	< .001
Residuals		29.810	21	1.420		
Actual force		8.594	1	8.594	6.949	0.015
Residuals		25.969	21	1.237		
Actuation method	Actual force	0.026	1	0.026	0.048	0.829
Residuals		11.287	21	0.537		

Note. Type III Sum of Squares

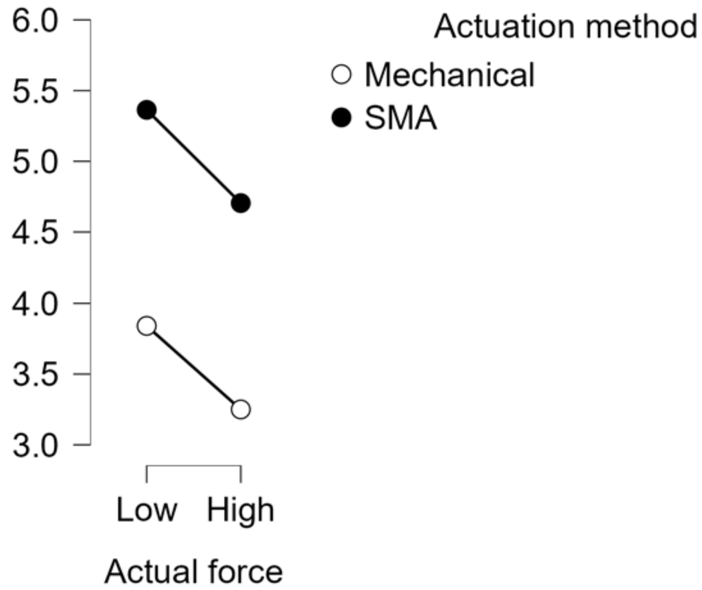
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	22.923	21	1.092		

Note. Type III Sum of Squares

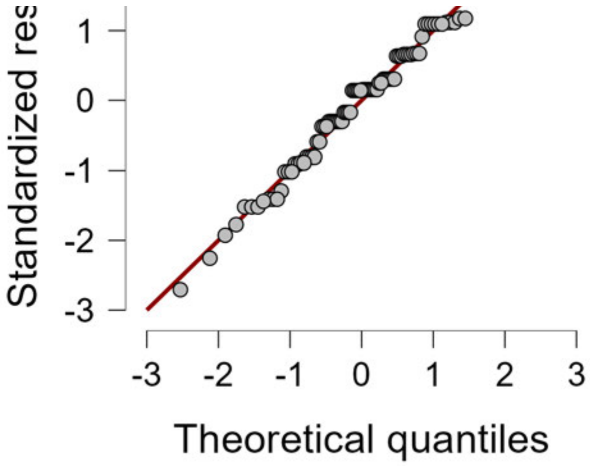
Descriptives

Descriptives plots



Assumption Checks

Q-Q Plot



Paired Samples T-Test - Perceived force

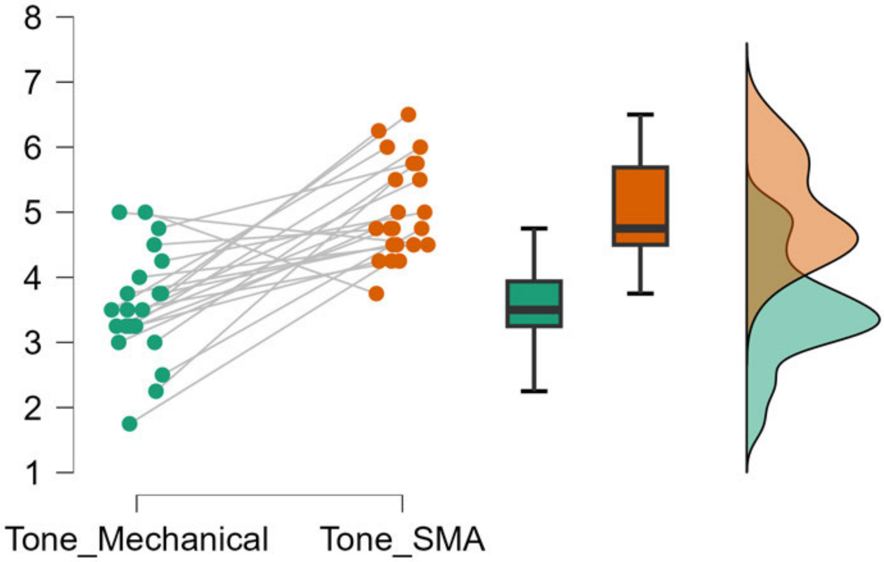
Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p
Tone_Mechanical	-	Tone_SMA	Student	-5.860		21	< .001
			Wilcoxon	12.500	-3.701		< .001
Tone_Mechanical_High	-	Tone_SMA_High	Student	-4.716		21	< .001
			Wilcoxon	23.500	-3.344		< .001
Tone_Mechanical_Low	-	Tone_SMA_Low	Student	-5.293		21	< .001
			Wilcoxon	12.000	-3.472		< .001
Tone_Mechanical_High	-	Tone_Mechanical_Low	Student	-2.890		21	0.009
			Wilcoxon	33.000	-2.495		0.012
Tone_SMA_High	-	Tone_SMA_Low	Student	-1.907		21	0.070
			Wilcoxon	44.500	-1.786		0.076

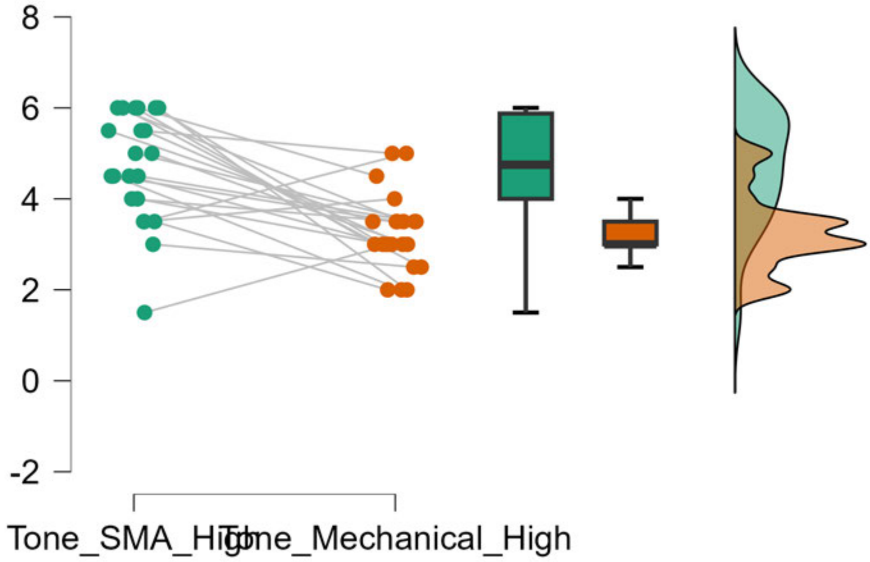
Descriptives

Raincloud Plots

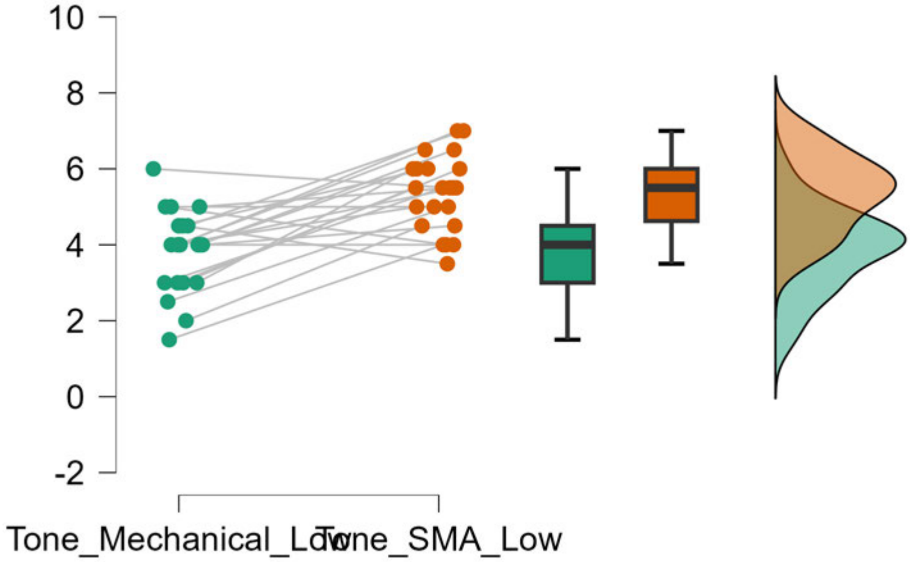
Tone_Mechanical - Tone_SMA



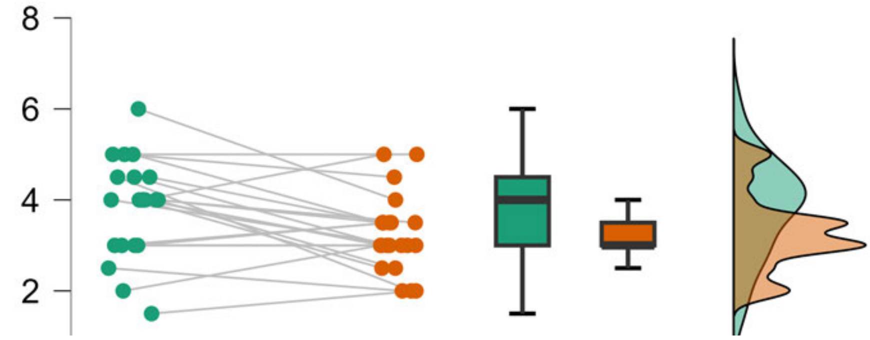
Tone_Mechanical_High - Tone_SMA_High



Tone_Mechanical_Low - Tone_SMA_Low

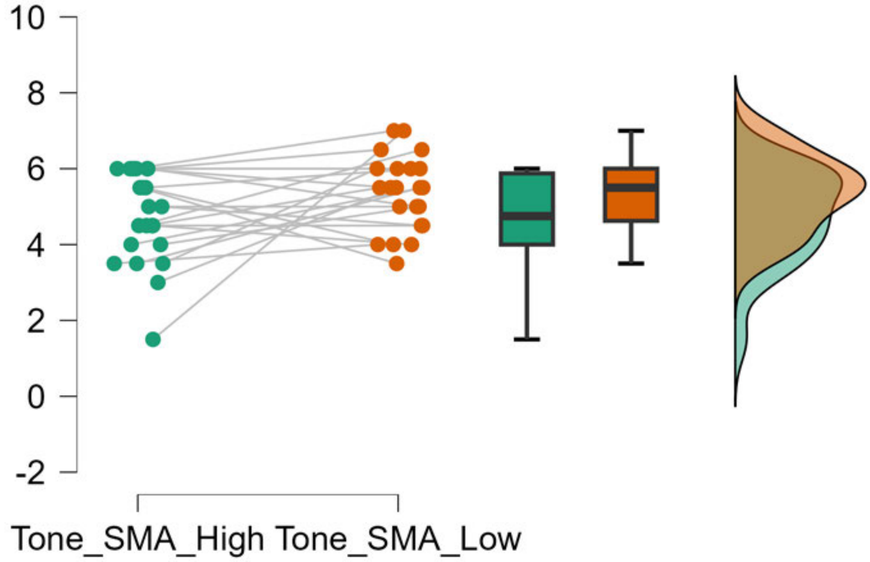


Tone_Mechanical_High - Tone_Mechanical_Low



Tone_Mechanical_Low Tone_Mechanical_High

Tone_SMA_High - Tone_SMA_Low



Results

Stroking - Humanlikeness

Repeated Measures ANOVA - Humanlikeness

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		77.344	1	77.344	36.525	< .001
Residuals		44.469	21	2.118		
Actual speed		0.230	1	0.230	0.356	0.557
Residuals		13.582	21	0.647		
Actuation method	Actual speed	0.480	1	0.480	0.680	0.419
Residuals		14.832	21	0.706		

Note. Type III Sum of Squares

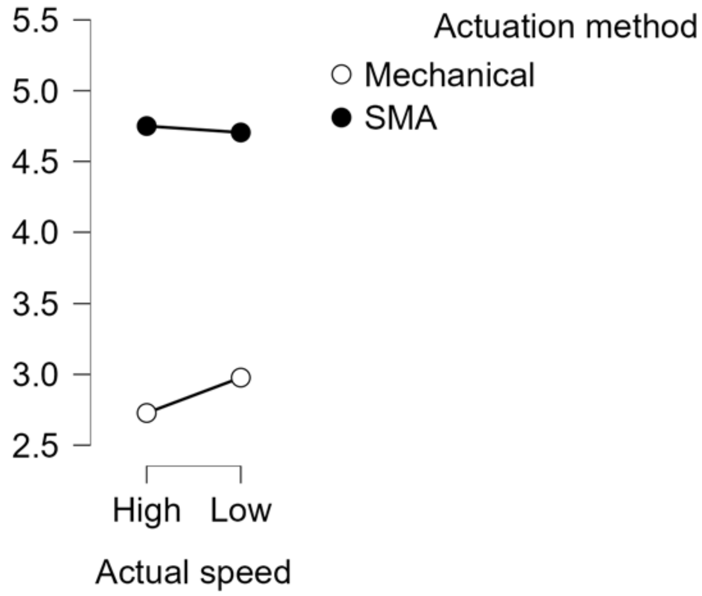
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	48.923	21	2.330		

Note. Type III Sum of Squares

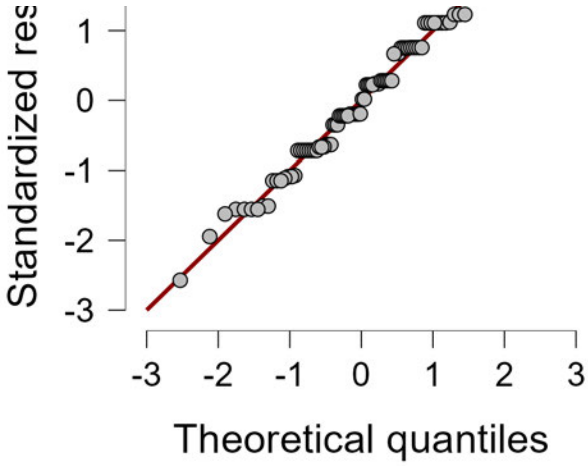
Descriptives

Descriptives plots



Assumption Checks

Q-Q Plot



Paired Samples T-Test - Humanlikeness

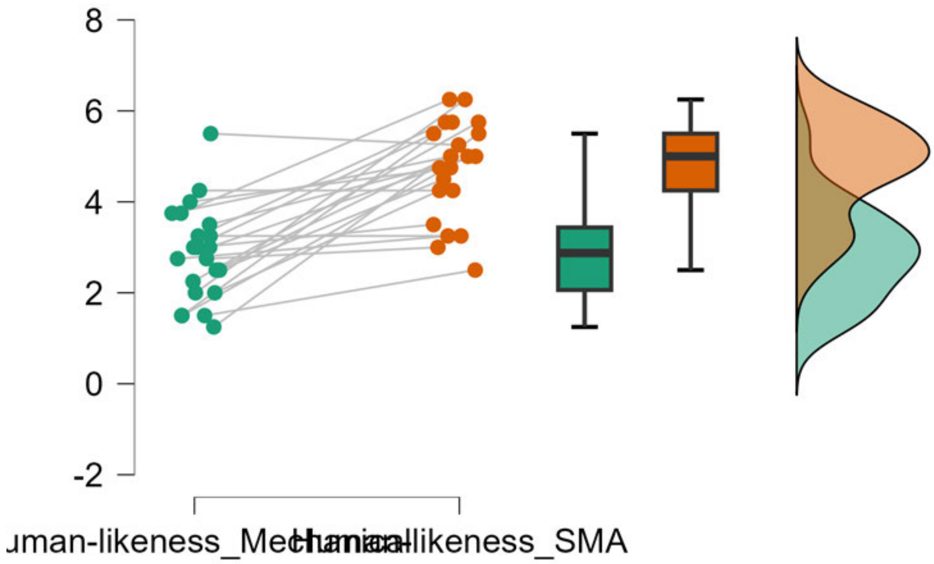
Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p
Human-likeness_Mechanical	-	Human-likeness_SMA	Student	-6.044		21	< .001
			Wilcoxon	1.500	-3.864		< .001
Human-likeness_Mechanical_High	-	Human-likeness_SMA_High	Student	-5.649		21	< .001
			Wilcoxon	7.000	-3.771		< .001
Human-likeness_Mechanical_Low	-	Human-likeness_SMA_Low	Student	-4.819		21	< .001
			Wilcoxon	20.000	-3.458		< .001

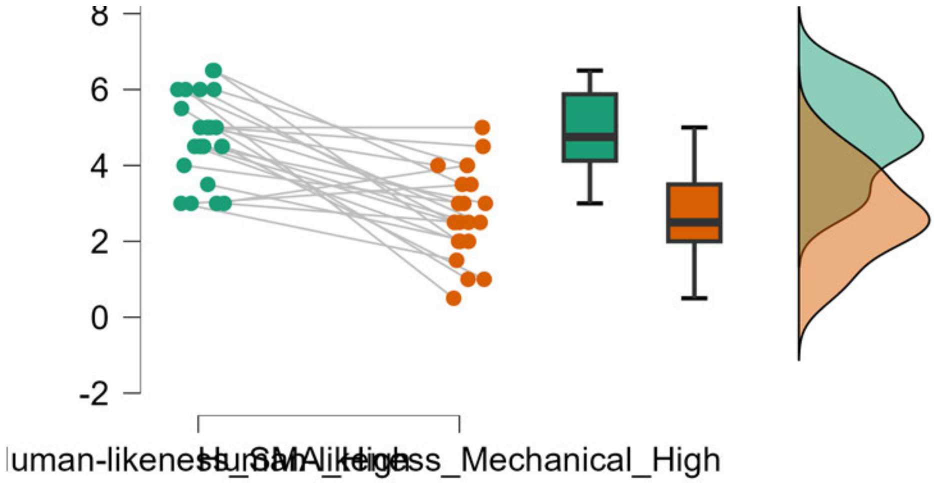
Descriptives

Raincloud Plots

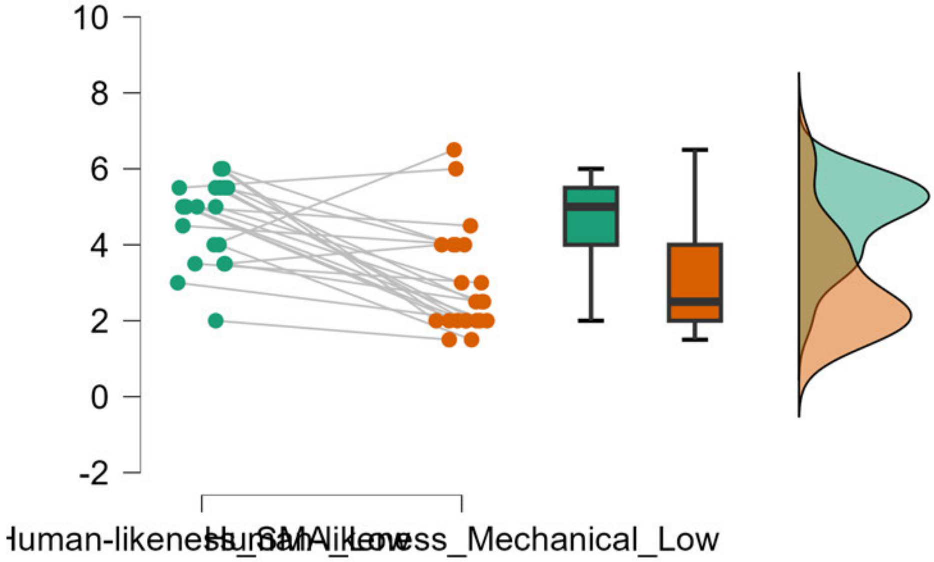
Human-likeness_Mechanical - Human-likeness_SMA



Human-likeness_Mechanical_High - Human-likeness_SMA_High



Human-likeness_Mechanical_Low - Human-likeness_SMA_Low



Results

Stroking - Intensity

Repeated Measures ANOVA - Intensity

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		13.136	1	13.136	14.433	0.001
Residuals		19.114	21	0.910		
Actual speed		2.227	1	2.227	2.789	0.110
Residuals		16.773	21	0.799		
Actuation method	Actual speed	0.409	1	0.409	0.542	0.470
Residuals		15.841	21	0.754		

Note. Type III Sum of Squares

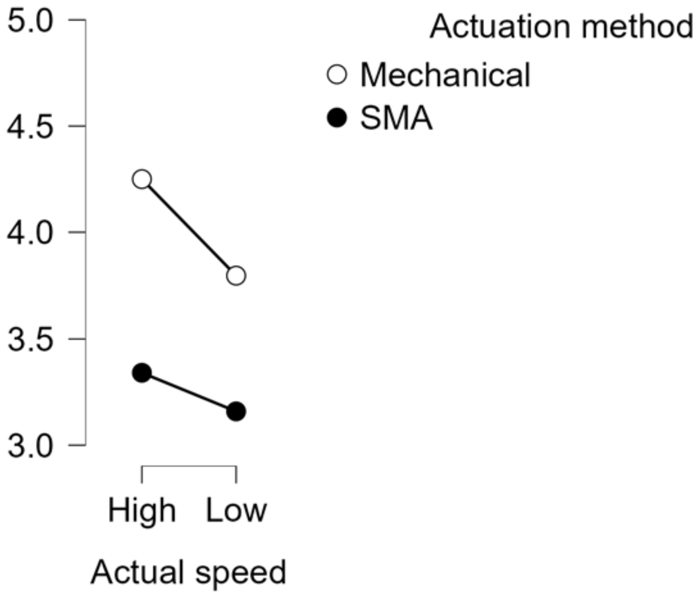
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	41.864	21	1.994		

Note. Type III Sum of Squares

Descriptives

Descriptives plots



Paired Samples T-Test - Intensity

Paired Samples T-Test

Measure 1	Measure 2	t	df	p

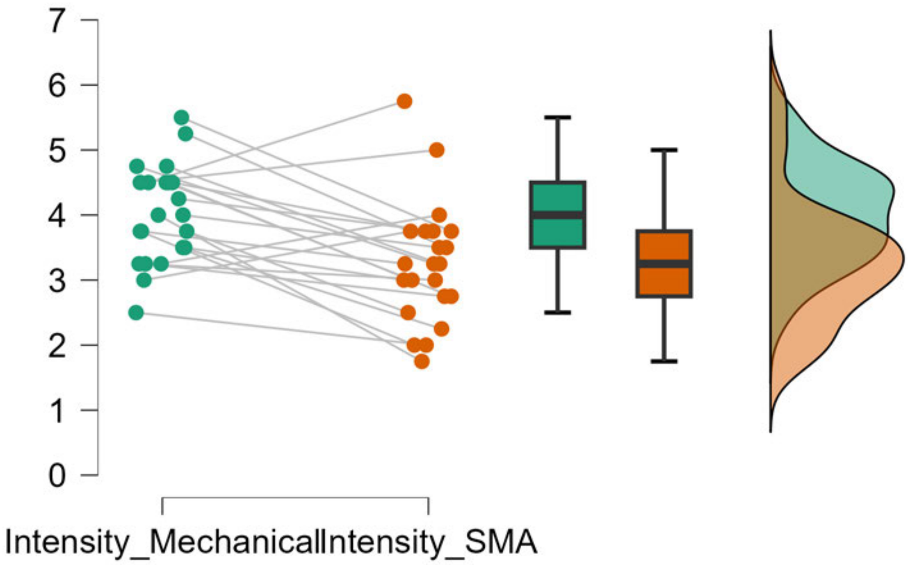
Intensity_Mechanical	-	Intensity_SMA	3.799	21	0.001
Intensity_Mechanical_High	-	Intensity_SMA_High	2.782	21	0.011
Intensity_Mechanical_Low	-	Intensity_SMA_Low	3.014	21	0.007

Note. Student's t-test.

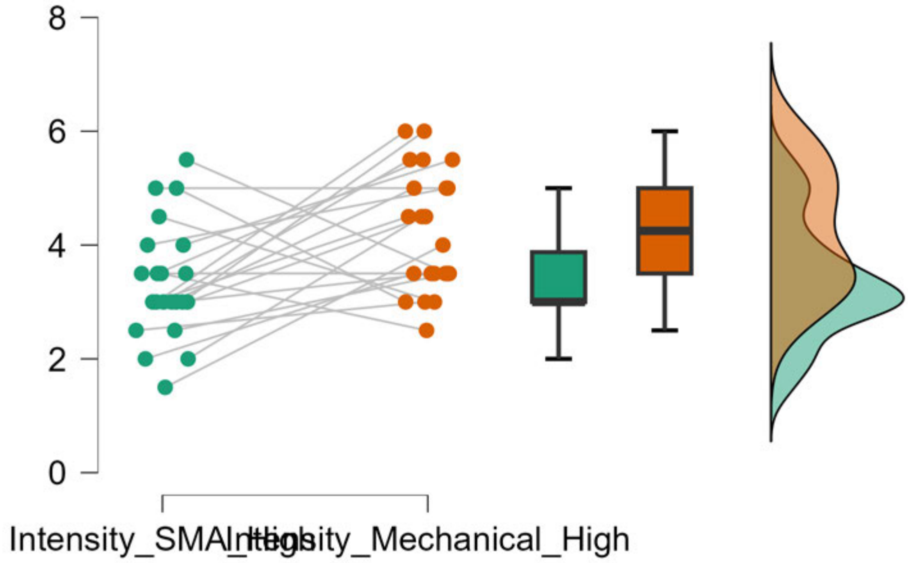
Descriptives

Raincloud Plots

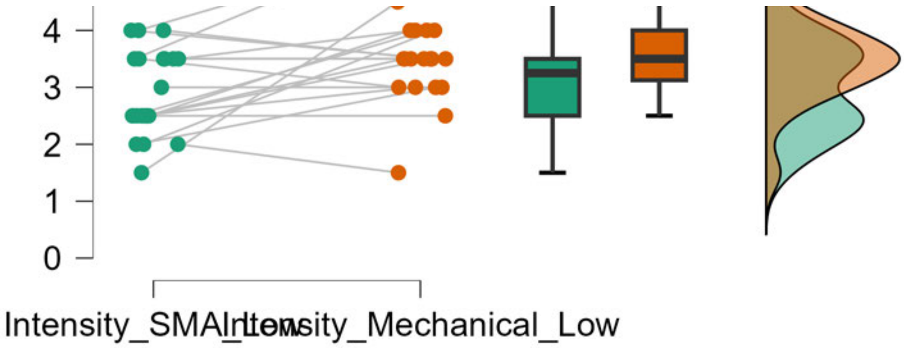
Intensity_Mechanical - Intensity_SMA



Intensity_Mechanical_High - Intensity_SMA_High



Intensity_Mechanical_Low - Intensity_SMA_Low



4
3
2
1
0
Intensity_SMA_Low
Intensity_Mechanical_Low

Results Stroking - Pleasantness

Repeated Measures ANOVA - Pleasantness

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		25.102	1	25.102	23.801	< .001
Residuals		22.148	21	1.055		
Actual speed		2.909	1	2.909	4.852	0.039
Residuals		12.591	21	0.600		
Actuation method	Actual speed	0.557	1	0.557	1.888	0.184
Residuals		6.193	21	0.295		

Note. Type III Sum of Squares

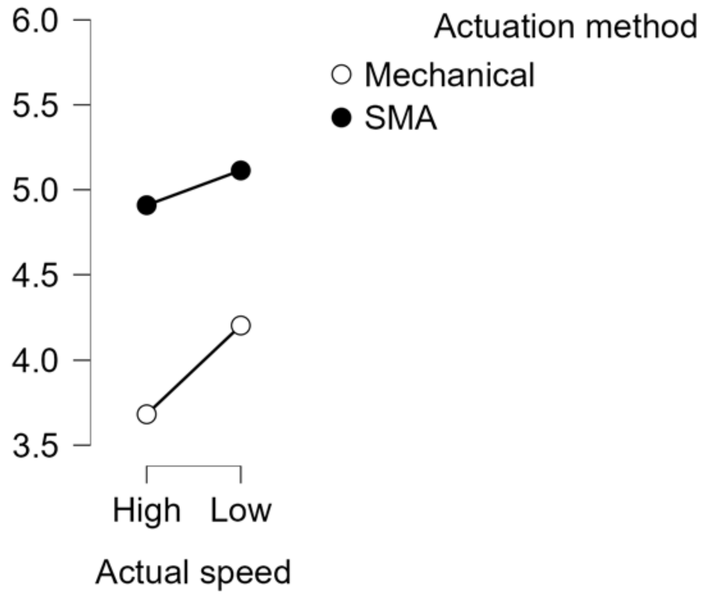
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	42.455	21	2.022		

Note. Type III Sum of Squares

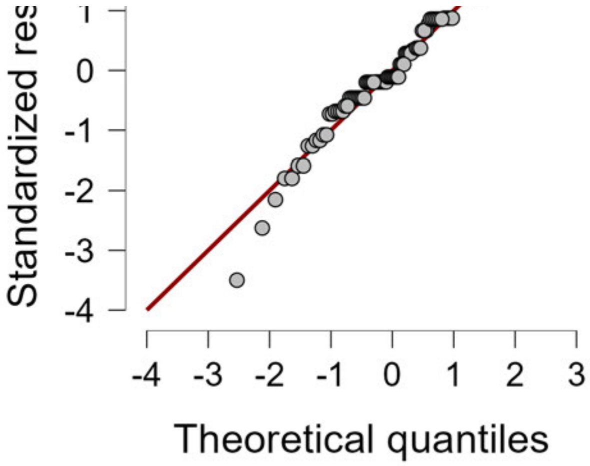
Descriptives

Descriptives plots



Assumption Checks

Q-Q Plot



Paired Samples T-Test - Pleasantness

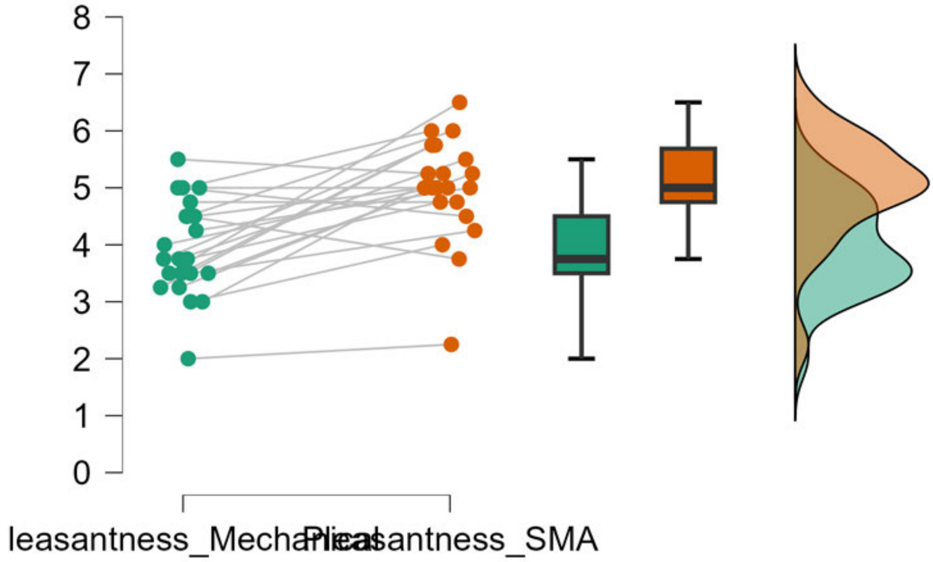
Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p
Pleasantness_Mechanical	-	Pleasantness_SMA	Student	-4.879		21	< .001
			Wilcoxon	11.000	-3.509		< .001
Pleasantness_Mechanical_High	-	Pleasantness_SMA_High	Student	-4.405		21	< .001
			Wilcoxon	18.000	-3.248		0.001
Pleasantness_Mechanical_Low	-	Pleasantness_SMA_Low	Student	-4.283		21	< .001
			Wilcoxon	21.000	-3.136		0.002
Pleasantness_Mechanical_High	-	Pleasantness_Mechanical_Low	Student	-2.215		21	0.038
			Wilcoxon	38.000	-1.823		0.069
Pleasantness_SMA_High	-	Pleasantness_SMA_Low	Student	-1.278		21	0.215
			Wilcoxon	38.000	-1.250		0.213

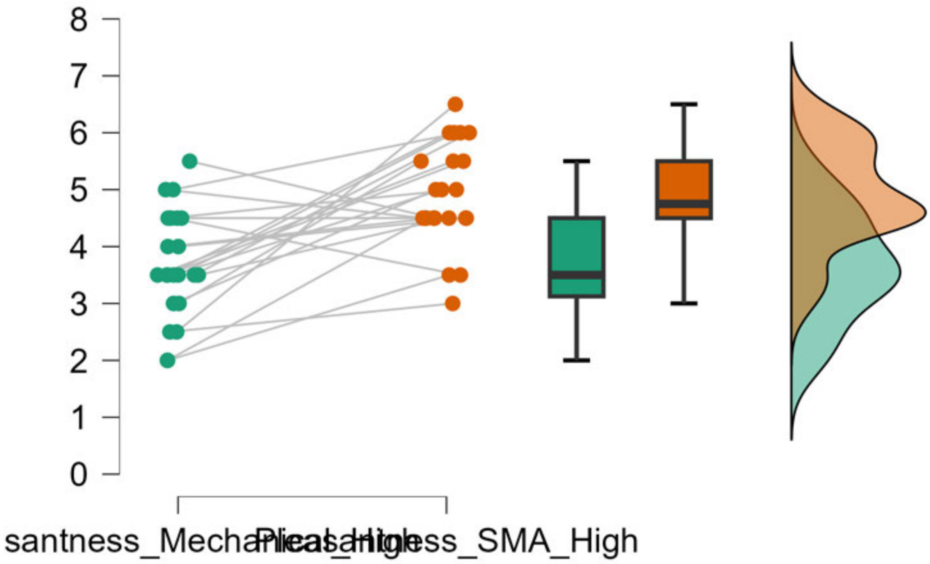
Descriptives

Raincloud Plots

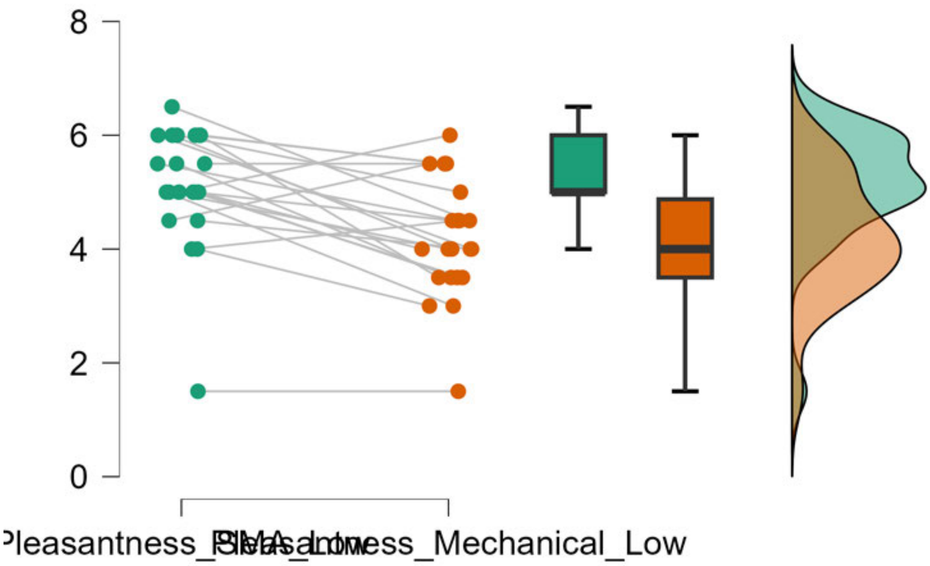
Pleasantness_Mechanical - Pleasantness_SMA



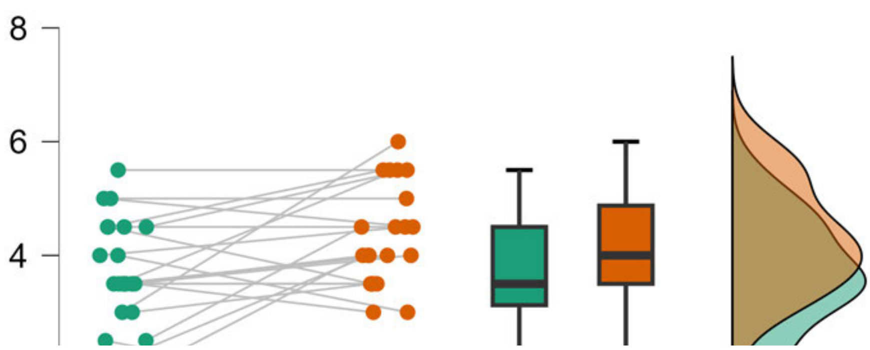
Pleasantness_Mechanical_High - Pleasantness_SMA_High



Pleasantness_Mechanical_Low - Pleasantness_SMA_Low

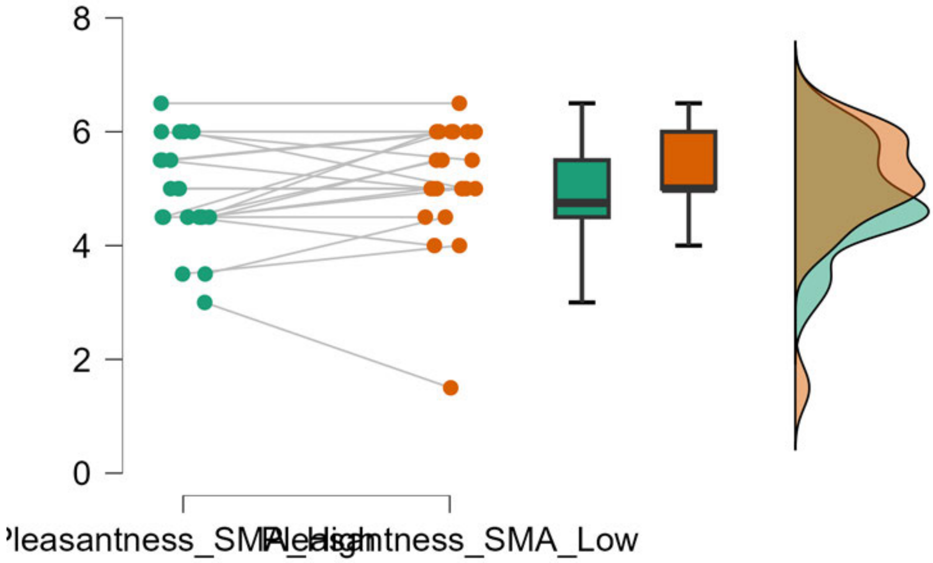


Pleasantness_Mechanical_High - Pleasantness_Mechanical_Low



santness_MecPleasantness_Mechanical_Low

Pleasantness_SMA_High - Pleasantness_SMA_Low



Results

Stroking - Perceived speed

Repeated Measures ANOVA - Perceived speed

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		10.227	1	10.227	4.531	0.045
Residuals		47.398	21	2.257		
Actual speed		13.920	1	13.920	33.584	< .001
Residuals		8.705	21	0.415		
Actuation method	Actual speed	3.284	1	3.284	5.170	0.034
Residuals		13.341	21	0.635		

Note. Type III Sum of Squares

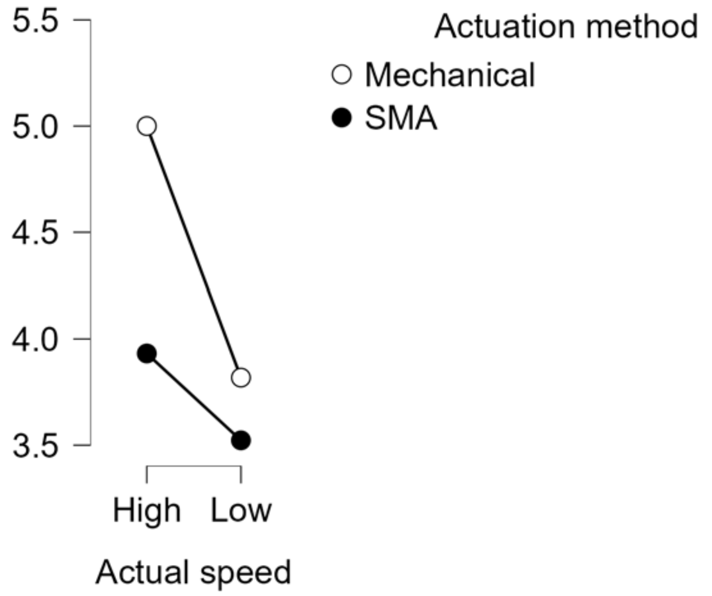
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	30.216	21	1.439		

Note. Type III Sum of Squares

Descriptives

Descriptives plots



Paired Samples T-Test - Perceived speed

Paired Samples T-Test

Measure 1	Measure 2	t	df	p

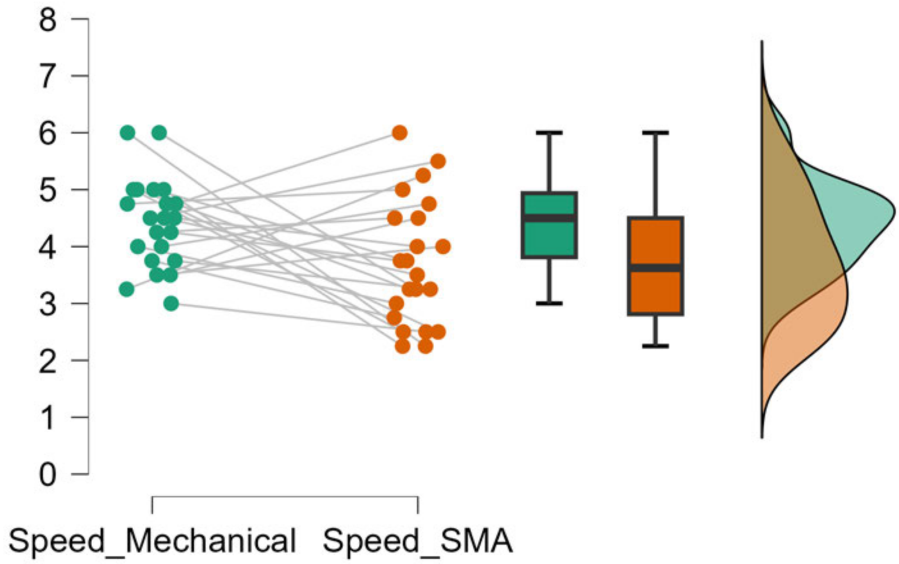
Speed_Mechanical	-	Speed_SMA	2.129	21	0.045
Speed_Mechanical_High	-	Speed_SMA_High	3.037	21	0.006
Speed_Mechanical_Low	-	Speed_SMA_Low	0.792	21	0.437
Speed_Mechanical_High	-	Speed_Mechanical_Low	4.617	21	< .001
Speed_SMA_High	-	Speed_SMA_Low	2.365	21	0.028

Note. Student's t-test.

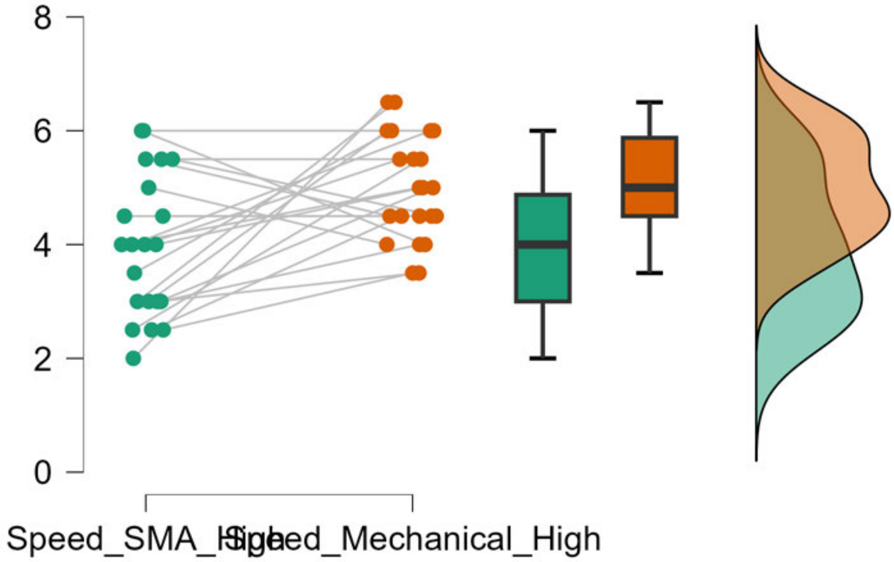
Descriptives

Raincloud Plots

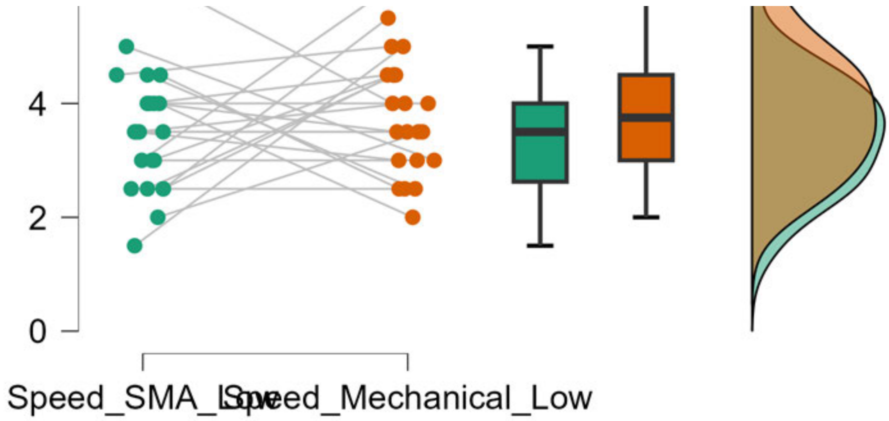
Speed_Mechanical - Speed_SMA



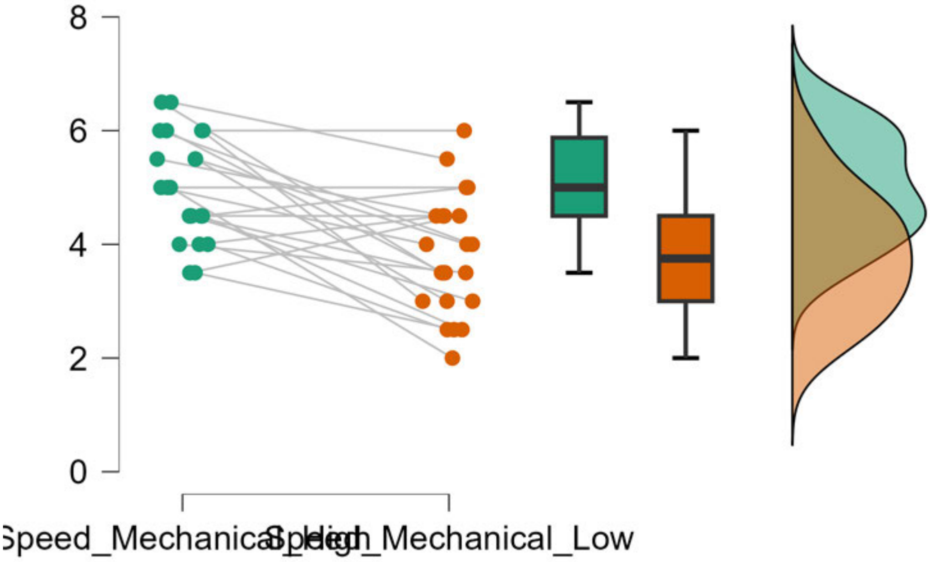
Speed_Mechanical_High - Speed_SMA_High



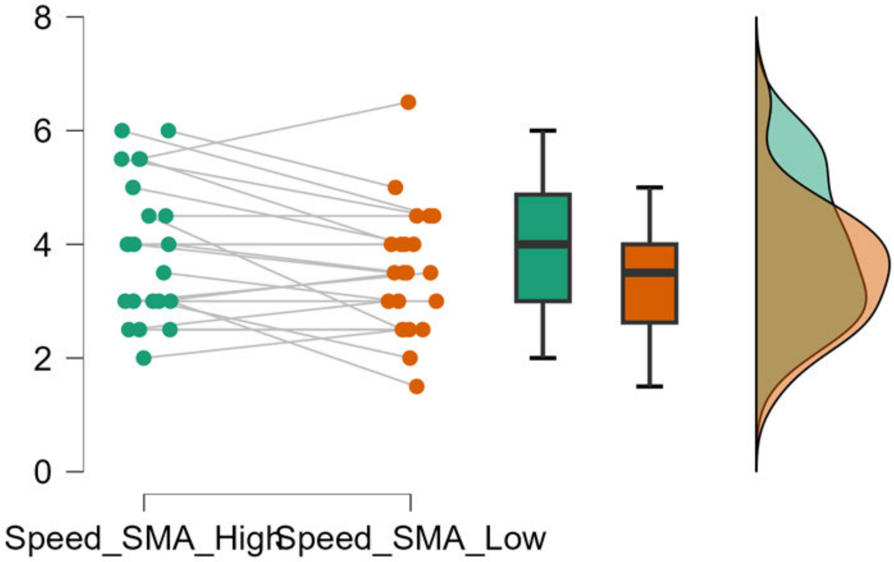
Speed_Mechanical_Low - Speed_SMA_Low



Speed_Mechanical_High - Speed_Mechanical_Low



Speed_SMA_High - Speed_SMA_Low



Results

Stroking - Feeling

Repeated Measures ANOVA - Tone

Within Subjects Effects

Cases		Sum of Squares	df	Mean Square	F	p
Actuation method		15.139	1	15.139	19.657	< .001
Residuals		16.173	21	0.770		
Actual speed		6.276	1	6.276	14.583	0.001
Residuals		9.037	21	0.430		
Actuation method	Actual speed	0.639	1	0.639	2.366	0.139
Residuals		5.673	21	0.270		

Note. Type III Sum of Squares

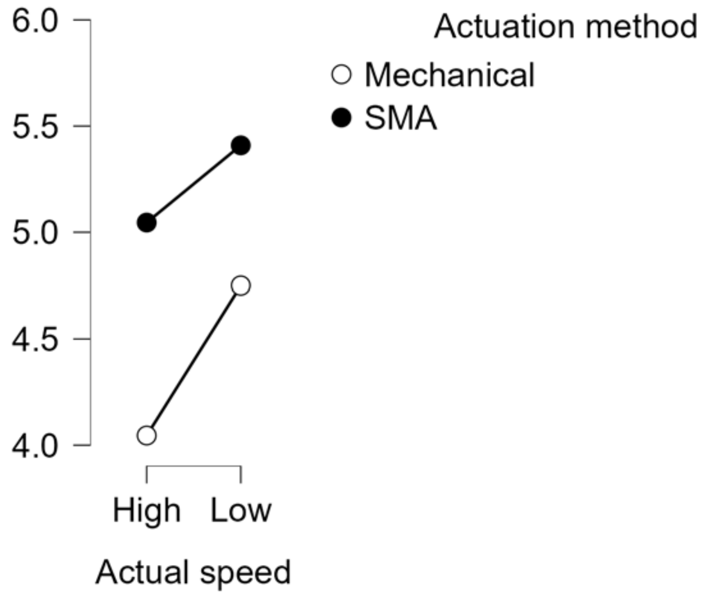
Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	31.219	21	1.487		

Note. Type III Sum of Squares

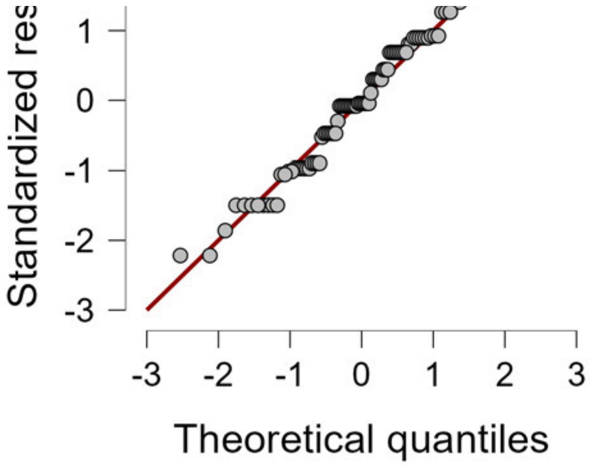
Descriptives

Descriptives plots



Assumption Checks

Q-Q Plot



Paired Samples T-Test - Tone

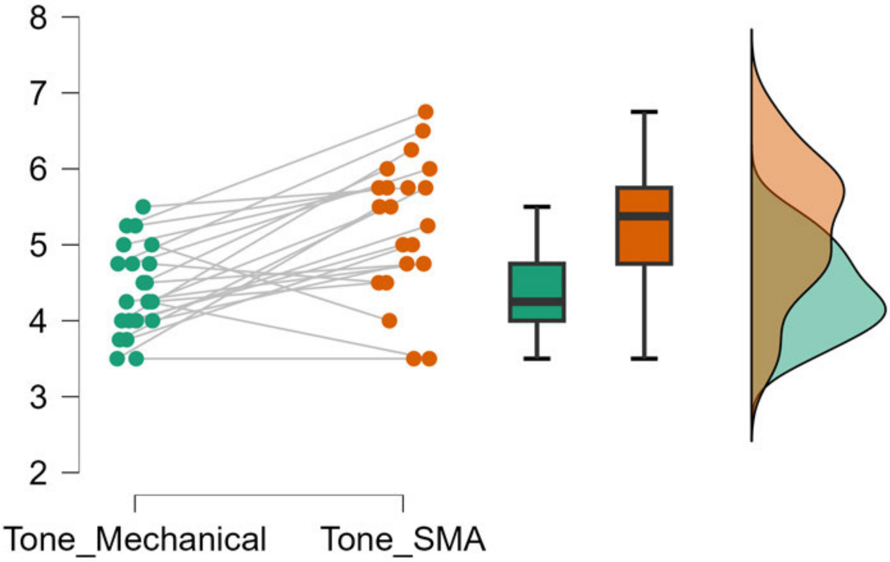
Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p
Tone_Mechanical	-	Tone_SMA	Student	-4.434		21	< .001
			Wilcoxon	21.000	-3.285		0.001
Tone_Mechanical_High	-	Tone_SMA_High	Student	-3.892		21	< .001
			Wilcoxon	21.000	-2.978		0.003
Tone_Mechanical_Low	-	Tone_SMA_Low	Student	-3.900		21	< .001
			Wilcoxon	13.000	-3.006		0.003
Tone_Mechanical_High	-	Tone_Mechanical_Low	Student	-3.691		21	0.001
			Wilcoxon	13.500	-2.818		0.005
Tone_SMA_High	-	Tone_SMA_Low	Student	-2.203		21	0.039
			Wilcoxon	23.000	-2.101		0.034

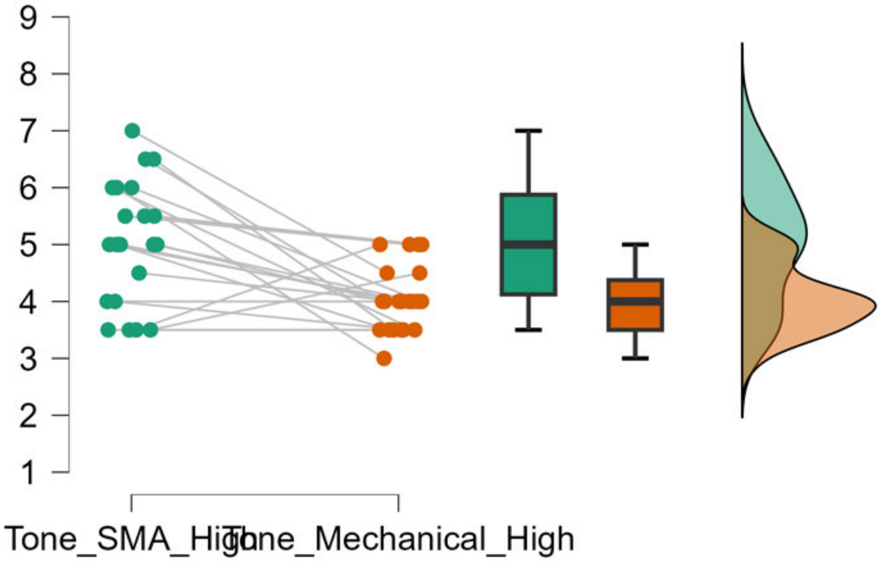
Descriptives

Raincloud Plots

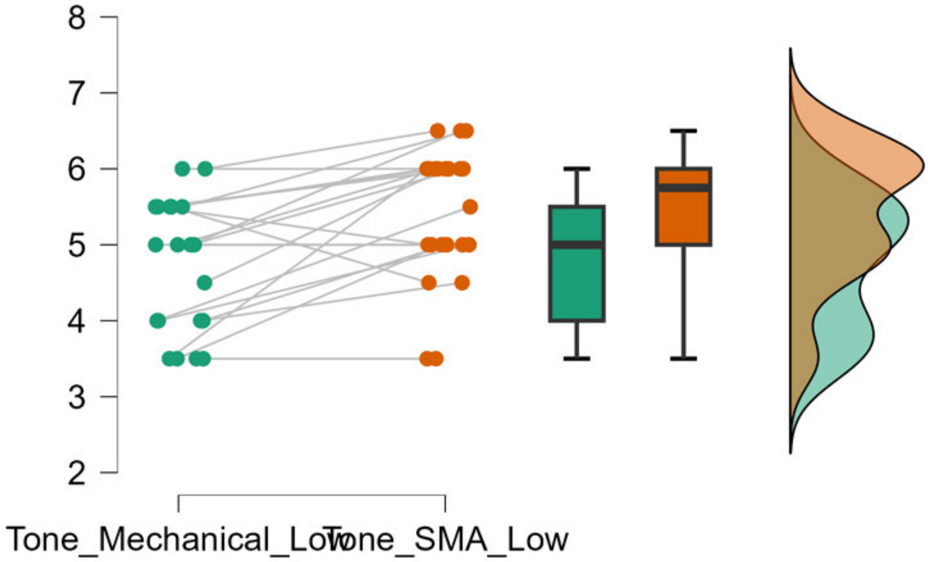
Tone_Mechanical - Tone_SMA



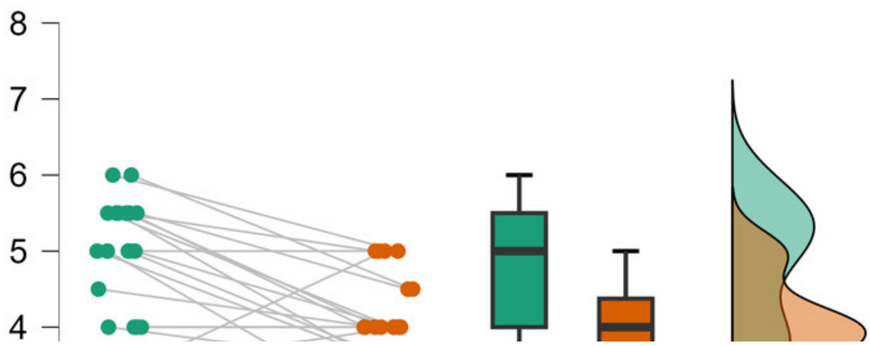
Tone_Mechanical_High - Tone_SMA_High



Tone_Mechanical_Low - Tone_SMA_Low

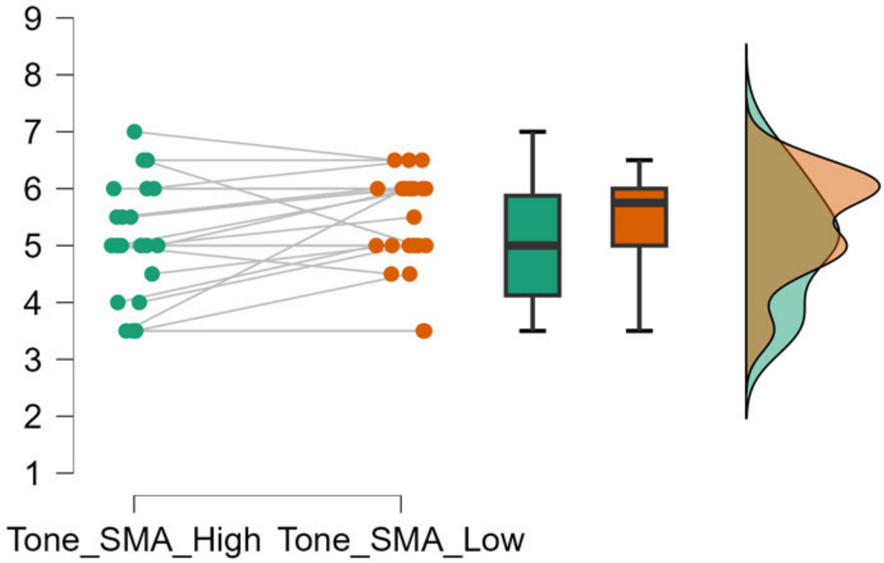


Tone_Mechanical_High - Tone_Mechanical_Low



Tone_Mechanical_Low Tone_Mechanical_High

Tone_SMA_High - Tone_SMA_Low



Appendix I – device impression answers

Participant (P1/P30)	Sensation	Actuation	Wearable	Disruptive	Appearance	Anxiety	Impairment	Movement	Weight	Change	Ergonomics	Attachment	Harm
P1	Squeeze	Mechanical	1	2	2	1	3	3	5	4	3	6	5
P1	Stroking	SMA	1	5	2	3	1	2	6	1	2	5	4
P2	Stroking	SMA	1	5	4	2	2	1	4	3	3	5	6
P2	Squeeze	Mechanical	1	3	3	5	2	3	3	3	6	5	7
P3	Stroking	Mechanical	2	5	1	7	6	7	7	3	6	7	7
P3	Squeeze	SMA	7	6	7	7	7	6	7	7	7	7	7
P4	Squeeze	SMA	5	6	3	4	2	3	3	2	6	5	3
P4	Stroking	SMA	1	3	1	5	1	1	5	3	4	2	3
P5	Stroking	SMA	6	2	4	3	3	3	6	3	5	6	7
P5	Squeeze	Mechanical	2	3	2	6	4	5	3	2	7	6	7
P6	Squeeze	Mechanical	1	2	1	3	2	3	3	4	6	6	6
P6	Stroking	Mechanical	1	2	1	6	2	2	2	2	2	5	7
P7	Stroking	SMA	2	3	5	6	2	2	5	5	4	3	6
P7	Squeeze	Mechanical	5	3	5	6	5	3	5	4	5	5	5
P8	Squeeze	SMA	4	3	5	1	3	6	6	6	7	6	7
P8	Stroking	Mechanical	2	3	3	6	2	2	4	6	3	6	7
P9	Stroking	Mechanical	3	3	1	6	3	6	2	6	2	2	7
P9	Squeeze	SMA	7	6	6	5	7	5	7	7	6	5	7
P10	Squeeze	Mechanical	2	1	2	5	4	2	4	5	6	6	7
P10	Stroking	Mechanical	2	3	3	4	4	3	3	4	6	6	7
P11	Stroking	SMA	2	3	3	2	1	2	5	3	3	3	6
P11	Squeeze	Mechanical	3	2	2	5	3	3	3	3	6	3	7
P12	Squeeze	Mechanical	2	2	3	4	1	6	7	5	7	7	6
P12	Stroking	Mechanical	2	3	2	3	2	3	6	4	2	6	7
P13	Stroking	SMA	2	4	3	6	1	2	7	6	7	6	4
P13	Squeeze	SMA	6	3	6	3	7	6	7	7	3	4	6
P14	Squeeze	SMA	6	7	7	3	7	7	7	7	7	7	7
P14	Stroking	SMA	2	7	3	5	4	3	6	5	6	7	7
P15	Stroking	Mechanical	3	6	2	7	6	6	2	7	6	5	7
P15	Squeeze	SMA	6	6	4	4	6	6	6	4	6	6	7
P16	Squeeze	Mechanical	3	5	3	6	3	6	6	7	6	7	7
P16	Stroking	SMA	2	3	3	6	2	3	6	7	5	5	7
P17	Stroking	SMA	5	6	6	6	3	3	6	3	5	5	7
P17	Squeeze	SMA	7	7	7	6	7	7	7	6	7	4	7
P18	Squeeze	SMA	5	5	6	7	7	7	7	3	7	5	6
P18	Stroking	Mechanical	2	5	2	7	3	3	7	3	6	5	5
P19	Stroking	Mechanical	2	1	6	6	2	2	7	6	2	3	7
P19	Squeeze	Mechanical	2	2	6	6	2	2	6	5	3	2	2
P20	Squeeze	SMA	6	2	3	3	7	6	7	6	7	7	7
P20	Stroking	SMA	2	3	2	6	4	2	7	1	2	7	6
P21	Stroking	Mechanical	5	3	6	5	3	6	5	3	6	6	7
P21	Squeeze	Mechanical	2	3	6	5	3	7	6	7	7	7	7
P22	Squeeze	Mechanical	1	1	2	2	1	1	4	2	6	5	3
P22	Stroking	SMA	1	1	1	2	1	1	4	3	5	3	2
P1	Squeeze	SMA	6	3	5	5	6	6	7	6	7	6	6
P1	Stroking	Mechanical	1	3	3	2	2	2	4	2	2	6	4
P2	Stroking	Mechanical	1	6	3	5	3	2	2	3	4	4	6
P2	Squeeze	SMA	5	5	6	5	5	6	5	5	6	6	7
P3	Stroking	SMA	6	5	3	7	2	2	7	3	3	7	7
P3	Squeeze	Mechanical	2	3	1	7	6	6	7	2	6	7	7
P4	Squeeze	Mechanical	3	6	2	4	2	3	5	7	3	7	7
P4	Stroking	Mechanical	3	3	3	5	2	2	6	5	6	4	7
P5	Stroking	Mechanical	2	3	4	3	2	5	3	3	5	3	7
P5	Squeeze	SMA	7	7	7	5	6	7	6	7	7	7	7
P6	Squeeze	SMA	6	5	6	3	7	7	6	6	6	7	6
P6	Stroking	SMA	1	2	2	3	2	2	6	3	5	5	6
P7	Stroking	Mechanical	5	5	5	6	3	3	3	5	5	5	6
P7	Squeeze	SMA	6	4	6	6	6	6	6	4	6	6	6
P8	Squeeze	Mechanical	1	2	5	6	1	2	4	4	5	5	7
P8	Stroking	SMA	1	1	1	3	2	1	5	3	6	3	6
P9	Stroking	SMA	1	2	1	3	1	1	6	4	2	1	3
P9	Squeeze	Mechanical	1	2	1	2	1	2	4	6	3	3	2
P10	Squeeze	SMA	4	5	4	3	5	6	7	5	6	5	7
P10	Stroking	SMA	2	2	3	4	2	1	6	3	6	4	6
P11	Stroking	Mechanical	5	3	3	2	2	3	6	5	6	6	7
P11	Squeeze	SMA	5	5	4	5	5	5	6	6	6	6	6
P12	Squeeze	SMA	7	6	6	7	7	7	7	7	7	7	7
P12	Stroking	SMA	1	5	2	2	1	1	7	3	5	5	7
P13	Stroking	Mechanical	2	4	3	6	5	6		6	6	6	7
P13	Squeeze	Mechanical	2	2	4	5	3	3	6	6	6	6	7
P14	Squeeze	Mechanical	3	2	3	6	5	7	7	7	7	7	6
P14	Stroking	Mechanical	2	6	3	4	4	5	3	5	6	7	7
P15	Stroking	SMA	3	3	3	7	1	1	6	3	2	5	6
P15	Squeeze	Mechanical	2	3	2	3	2	5	6	5	6	4	7
P16	Squeeze	SMA	6	3	6	4	7	5	7	7	7	3	7
P16	Stroking	Mechanical	2	2	2	6	3	3	6	7	4	2	7
P17	Stroking	Mechanical	6	6	7	6	6	5	6	6	6	5	5
P17	Squeeze	Mechanical	6	5	7	6	6	5	6	6	6	5	6
P18	Squeeze	Mechanical	2	2	3	3	2	2	7	3	7	3	7
P18	Stroking	SMA	2	1	6	6	1	2	7	2	2	3	6
P19	Stroking	SMA	1	4	5	6	1	1	6	2	1	2	3
P19	Squeeze	SMA	4	2	6	6	3	2	7	6	2	1	2
P20	Squeeze	Mechanical	1	1	1	7	3	7	5	6	7	6	7
P20	Stroking	Mechanical	3	3	3	2	4	5	3	2	4	5	7
P21	Stroking	SMA	3	3	6	6	2	2	7	4	3	7	6
P21	Squeeze	SMA	7	6	7	5	7	7	7	7	7	7	7
P22	Squeeze	SMA	5	2	5	2	5	5	3	3	6	2	2
P22	Stroking	Mechanical	1	1	1	3	1	2	2	1	2	3	3