Master Thesis

Experiencing textures through touch technology

by

Adam Joost Meijer

Interaction Technology
Faculty of Electrical Engineering, Mathematics and Computer Science
University of Twente

Supervisor: **Angelika Mader**
Co-Supervisor: **Judith Weda**
External Examiner: **Jelle van Dijk**

June 2023

Acknowledgement

I would like to thank my supervisor Angelika and co-supervisor Judith for your feedback, support and guidance. We had a lot of meetings, almost one each week and this helped in keeping myself motivated. Furthermore, I would like to thank Dasha who helped me to depict my data and design a good study. I also would like to thank Daniel for thinking along and for making use of rooms and devices. Lastly, I would like to mention Laura A Dima for the inspiring sessions we had.

Abstract

The hedonic and arousing qualities of touching materials have been identified as a gap in the existing literature, particularly in relation to their implications for mediated social touch technology. Recent research has sparked debates regarding the softness dimension out of the five dimensions of texture. On top of that extending the social affective touch hypothesis by emphasizing the significant role played by both C-tactile touch and deep pressure in generating pleasant tactile sensations. In this research, a series of three studies were conducted using a McKibben sleeve, which utilizes pressure touch through pneumatic actuation. The aim of this research was to explore the effects of different pressures and textures on evoking affective sensations. Therefore a total of 17 textures were designed and selected to investigate which textures evoke which emotional response. Past research proposed, after an active touch experiment, that the perceived softness of a material consists of the properties of compliance, granularity, viscosity and furriness. Hence in this study, it was studied if these properties could be translated to passive touch. In the first study, participants were tasked with identifying 17 textures suitable for passive touch based on material properties compliance, granularity, viscosity, furriness, and softness. Subsequently, in a second study participants were asked to rate different pressure touches, varying in force and duration. Finally, in a third study, participants reported the emotional sensations evoked by three pre-validated textures. This evaluation was carried out using a check-all-that-apply list consisting of 25 items and the Emojigrid to capture affective responses. The findings revealed that the level of compliance had the most effect on the perceived softness of a texture. Moreover, both force and texture were found to impact the experience of passive pressure touch. These results serve as a foundation for the application of textures in mediated social touch technologies, as well as for further exploration of their potential use cases in the field of haptics.

Contents

1

Introduction

Since the COVID-19 pandemic, people have become acutely aware of how sociable we as humans are. We became more aware of the negative impact of the absence of touch in our day-to-day lives. Touch is a powerful tool in maintaining and engaging relationships, essential in parent-child and intimate romantic relationships, and crucial in patient care. Moreover, in patient care, being touched and physically close to the patient is very important as it favours recovery and pain reduction [34]. Beyond its social and emotional benefits, touch also has positive effects on our physiological and biochemical systems, including decreases in blood pressure and heart rate but also increases in oxytocin levels (love hormone) and decreases in cortisol levels (stress hormone) [16, 19, 20]. Furthermore, through touch one convey messages that can not be expressed with words. Already in 1971, Montagu [33] pointed out the importance and magnificence of touch in his book. As he stated that touch is ten times stronger than verbal or emotional contact, it affects almost everything we do and there is no other sense that can arouse you as touch can. Hertenstein et al. [22] showed that distinct emotions can be communicated via touch by varying in duration and intensity. Moreover, Kirsch et al. [29] studied the role of touch in communication and found that distinct intentions can be communicated by touch alone and that tactile behaviour provides new information about the perception of emotions. App et al. [2] found that touch is the preferred way to communicate intimacy (e.g. love, lust), while social status (e.g. pride, embarrassment) is preferably communicated by body actions and survival emotions (e.g. happiness and anger) via the face.

In today's world, much of our communication happens remotely through texting or calling, with visual and auditory senses being the primary modes of communication. Especially during long-distance communication, almost all technology focuses on the visual and auditory senses, but less progress is made in using haptic technology as the communication channel [44]. This is a big shortcoming since as described above, using tactile channels can greatly enhance our life and the way we communicate. A large field of research within haptic technology is about developing haptic wearables that are able to deliver affective touch at a distance. This concept is called mediated social touch, where tactile or kinesthetic interfaces are used to let people who are physically apart, have haptic communication [46]. Past research showed that even simple forms of mediated social touch can evoke affective feelings [44]. Currently, it is difficult to design fully functioning haptic devices that can successfully communicate the complexity of human touch [36]. These constraints are both hardware and psychologically-orientated. As haptic actuation technologies for example are bulky and noisy; and designing effective mediated haptic interactions requires in-depth knowledge of involved psychological mechanisms in the perception of affective touch [44]. Still, a lot of research and improvement in haptic technology has to be done to fully utilize touch as a communication channel.

Despite the importance of touch in human-human interactions, exploring and interacting with objects is of vital importance for us to interact with the world. With the sense of touch, we can discriminate material and object properties, but touch also has hedonic and arousing qualities [14, 32, 43]. Already in 1895 the tactile experience of texture is explored by Major [31] and reported that soft and smooth materials were unanimously perceived as pleasant and materials that were stiff, rough and coarse are perceived as unpleasant. This shows that textures evoke emotions upon touch, making it interesting to further explore what kind of emotions various textures can evoke. In summary, understanding the emotions different textures evoke will shed light and improve our tactile experiences.

1.1 Research Questions

In recent decades the perception of pleasant touch had been investigated by neuroscientists. They found that stimulating C-tactile sensory afferents, which are present in hairy skin, evoked pleasant sensations. For example slowly and gently stroking someone's arm is a type of social touch that activates these C-tactile afferents and hence stimulates pleasant sensations [32]. However, pressure touch is another form of pleasant touch that has been little studied, examples of this social touch are hugging or cuddling. Especially, little is known about the physiological foundation of the emotional benefits of pressure touch and how this relates to the pleasurable sensations that deep pressure can evoke [7]. Furthermore, as stated earlier textures can also evoke different emotions [14, 31, 43]. Therefore rising the question, which textures evoke which emotional response? This is a very broad question since there exist lots of different materials and objects, each having different material characteristics. Researchers have shown that textures can be described by five dimensions: warmness, softness, micro and macro roughness and stickiness [24]. Hereof most research has been done on the softness dimension and indicates that softness only correlates to the property of compliance, in other words, the deformation and elasticity of an object when subjected to an applied force. However, the definition of softness has been discussed lately. In an active touch study by [8], they found that softness is not only correlated to compliance but has multiple dimensions. Namely, it was discovered that softness covaries with the viscosity, granularity, furriness and compliance of a material.

Therefore the purpose of this study is to gain new insights into the emotional experience of the multiple dimensions of soft textures. As well as the affective response to various pressures. Whereby these stimuli will be passively applied using a haptic device to the forearm. This body location is selected thanks to its accessibility, acceptance and popularity of this body location. Hence the research questions and subquestions for this thesis are as follows:

Q1 What is the effect of passively received materials on the forearm, validated on compliance, viscosity, granularity, furriness and softness, on evoking emotions via a haptic device?

In order to answer the question above, the materials that will be passively applied had to be selected. Criteria therefore were that they had to fit the haptic device and the more diverse these materials, the wider they covered the textural qualities of compliance, viscosity, furriness and granularity. Moreover, when applying a material in the haptic device, upon contraction the pressure stimuli must still be felt. To compare the results of this study with the active touch study of Cavdan et al. [8], the correlations between these qualities will be investigated and compared. To conclude if the same qualities play an important role for soft materials in passive touch. As these qualities of soft texture are found in an active touch experiment it was unknown if these properties translated to passive touch. Hence, the following subquestions are generated to explore the effect of textures in passive touch:

- **SQ1 How are the qualities of soft materials (varying in compliance, granularity viscosity and furriness) perceived when passively applied to the forearm?**
  - **SQ1.1 How do passively applied materials (varying in compliance, granularity, viscosity and furriness) on the forearm relate to softness?**
  - **SQ1.2 How do passively applied materials (varying in compliance, granularity, viscosity and furriness) on the forearm relate to each other?**
  - **SQ1.3 What are representative and available soft materials that resemble these textural qualities in passive touch?**
    - **SQ1.3.1 How to select or design the material so that its properties and contraction can be well perceived in the apparatus used?**

In addition, the following second main question is derived to explore the effect of pressure in passive touch:

- **Q2 What is the effect of passively received pressure stimuli gestures, varying in force and duration, on the forearm in evoking affective responses?**

To answer this question, relevant parameters for pressure force and duration on the forearm in mediated social touch had to be obtained. Therefore the following subquestion is proposed:

- **SQ2 What are relevant values for pressure force and duration on the forearm in mediated social touch?**

In this thesis, multiple studies have been performed in order to give answers to all questions. In the next chapter, more background information will be elaborated to explain the four dimensions of soft textures found by Cavdan et al. [8] as well as the use of pressure to evoke emotional responses. Thereafter state-of-the-art haptic devices that use texture and or pressure touch to evoke affective responses are presented. Subsequently, a methodology chapter where the research design and setup of the studies are discussed. Followed by a chapter about the setup design where the design of textural stimuli is discussed likewise the values for force and duration for the pressure stimuli are determined. Hereafter the first study focusing on the validation of a set of textures is presented. Next, the second study about the affective response of different pressures is illustrated. Lastly, in the third study, the emotional experience of passively applied textures on the forearm is investigated. Each study chapter contains a discussion section to discuss the results. Finally, a general discussion can be found and as a final chapter a conclusion.

2

Background

In this chapter background literature about affective touch and material dimensions will be elaborated. Especially the recent developments in pleasurable touch called deep pressure touch and developments about material softness will be addressed. At first, classical and grounded theories will be explained after which the recent developments and shifts in the field of material dimensions and affective touch will be addressed.

2.1 Affective touch

Touch can be parted in discriminative and affective touch [32]. Where discriminative touch is related to exploratory information about tactile properties, such as distinctive, spatial and temporal localization [27]. This information is conducted by stimulating low-threshold mechanoreceptors on the skin that activate AB nerve fibers that are myelinated [10]. Affective touch, on the other hand, is related to emotion, thus the pleasant and unpleasant sensations evoked by touch [32]. This type of touch is triggered by stimulating low-threshold mechanoreceptive afferents that are unmyelinated called CT fibers, which are only present on hairy skin [10]. Moreover, this can be parted into optimal CT fiber activation, which is related to pleasant sensations, and non-optimal CT fiber activation which results in unpleasant sensations. In the field of neuroscience, the classical definition of affective touch is that of optimal CT fiber activation, which can be obtained with touch at velocities between 1-10 cm/s and with a temperature around that of the human skin. For example, slowly stroking the forearm. Slower or faster velocities will result in non-optimal nerve fiber activation and thus unpleasant sensations. To simulate such a stimulus, a brush is frequently used, thanks to its ideal characteristics of soft material and light force [45]. Currently, this classical affective touch hypothesis in social touch is under discussion, as AB fiber activation in discriminative touch also contributes to pleasant sensations [47] and studies indicate that CT afferents are also present on the glabrous skin [35]. What is certain is that affective touch is important in creating pleasant sensations and thus in evoking emotions.

Optimal CT fiber activation is not the only way to stimulate pleasant tactile sensations; in a recent study by Case et al. [7] a new type of pleasurable touch is studied, namely deep pressure touch. Some examples of this social touch are hugs, cuddling and massages. Previous studies on deep pressure touch have been found to reduce anxiety and increase calmness [21, 38]. Thereby Case et al. [7] demonstrated that oscillating deep pressure has similar affective effects to that of gentle C-tactile stroking. These similar affective effects were found in similar pleasantness and calmness ratings for both types of touch. However, the touch perception and cortical activation patterns for C-tactile and deep pressure touch are similar but distinct. Furthermore, they found a difference in peripheral sensory afferents that transduce these sensations. Therefore they propose “that gentle stroking and deep pressure are two primary sensory inputs for pleasant, rewarding social touch [7].” Thus expanding the social affective touch hypothesis by arguing that both C-tactile and deep pressure touch play an important role in pleasant tactile sensations. Overall, this research will further investigate the role of pressure in touch and the emotional responses it evokes.

2.2 Qualities of soft materials

In a study by Hollins et al. [24], they discovered that textures can be differentiated based on roughness, hardness, friction and warmness. Whereby roughness can be divided into macro and fine roughness, resulting in a total of five dimensions [11, 37], see Figure 1.

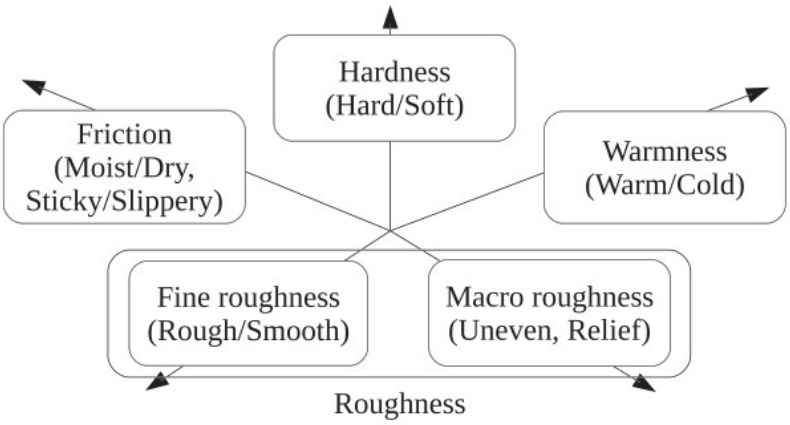

Figure 1: The five dimensions of textures [37].

Previous studies by Bergmann Tiest and Kappers [4], Hollins et al. [24] considered perceived roughness, hardness and friction as independent dimensions. Whereby the roughness dimension is related to the height differences on the surface of the material. Hardness is related to the elasticity of the material. In previous literature, the terms hardness or softness and compliance are intertwined and mean the same. Friction is related to the moistness and stickiness between the material and the skin, and warmness to the material’s heat capacity and thermal conductivity [3]. The dimensions of roughness and warmness can be perceived through static interaction, whereas hardness and friction have to be perceived through dynamic interaction [3]. Moreover, textures can be perceived either actively or passively. In passive touch, someone’s stationary skin is stimulated by an outside agent or surface. In active touch, a surface is explored by moving someone’s skin across the surface. Most past research is done on the roughness of a material whereby Hughes et al. [25] claimed that roughness is the most dominant attribute of textures in order to distinguish textures by touch. However recent research questions the five dimensions of textures, as they claim that the dimension of perceived softness has multiple dimensions instead of only hardness or compliance as argued previously. After using Principal Component Analysis for an active touch experiment, Cavdan et al. [8] discovered that perceived softness covaries with compliance, viscosity, granularity and furriness. To clarify see Figure 2 for a visual representation of these material characteristics.

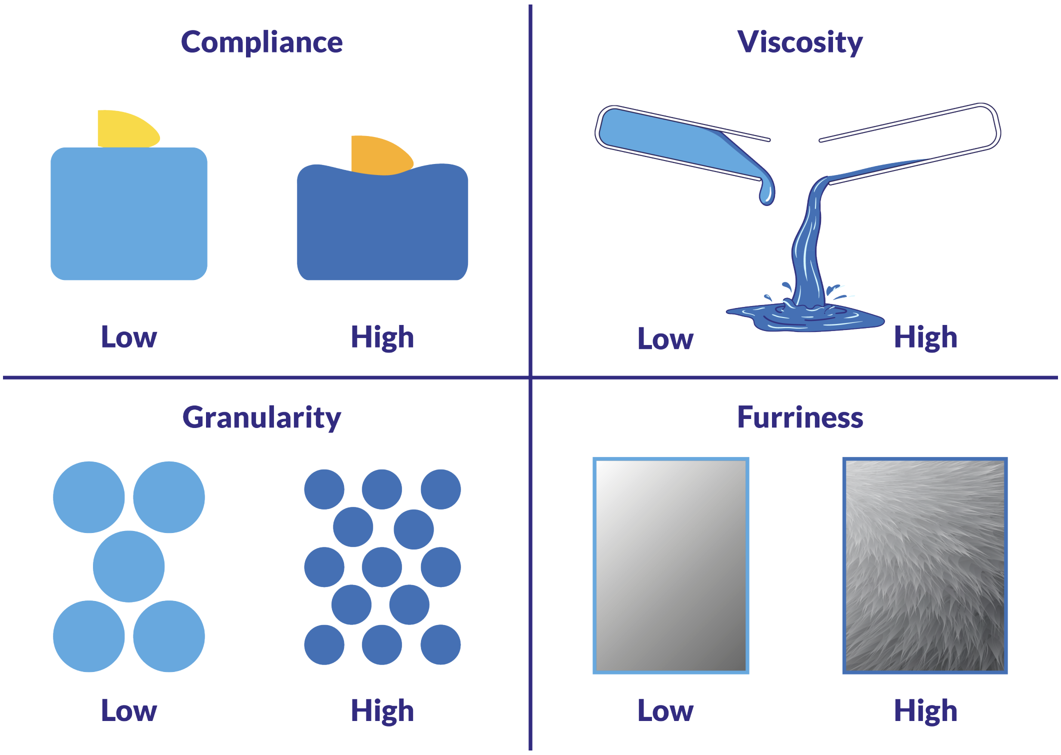

Figure 2: The four characteristics of softness.

In this research, they let participants freely explore materials by hand and found that soft materials were not only explored by applying pressure but by using multiple exploratory procedures like pulling and rubbing. Another surprising finding was that out of all the exploratory actions possible, participants always rub a material regardless of what material it is. Moreover, instead of a single movement, participants used combinations of movements to optimally explore the materials. In addition, in a recent study by Inoue et al. [26], two experiments were performed to test if concave objects of the same material, but with different sizes would be experienced as harder or softer. The findings of the first experiment suggested that the concaves of similar size and shape to the finger were judged as the softest. Whereby convexes were judged to be harder than flat or concave shapes. Additionally, in an earlier study by Hughes et al. [25] they state that observations indicate that perceived roughness is positively correlated with the downward force applied to this object. This could indicate that roughness and compliance are related to each other since the compressibility of a material is also correlated with the force applied to its object.

All these findings indicate that softness is not only correlated to hardness unlike previous studies argue, but that softness has multiple dimensions. Further research is needed to draw definite conclusions on the precise dimensions. However, since the four dimensions of softness [8] are discovered via active touch it will be interesting how this translates to passive touch. This study therefore further investigates the qualities of compliance, viscosity, granularity and furriness as dimensions for softness in passive touch.

3

State of the art

In this section, state of the art examples of recent haptic devices that use pressure and or texture as stimuli will be discussed. As well as mediated social touch studies where haptic devices were used to evoke emotions.

3.1 Haptic devices for mediated social touch that use pressure

Starting with the PneuSleeve of Zhu et al. [54], this is a haptic device that can be worn on the forearm and render three types of haptic stimuli to the user.

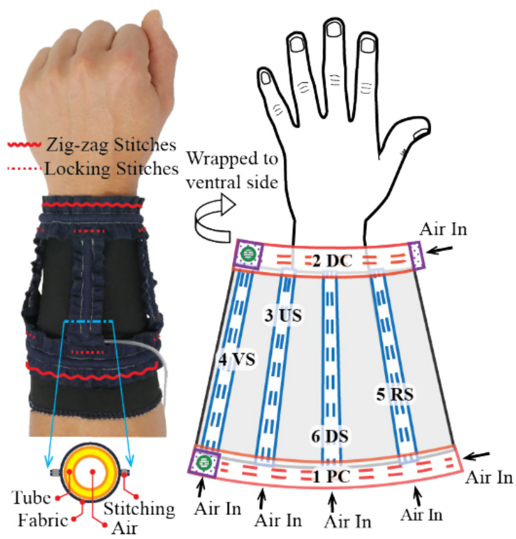

Figure 3: PnueSleeve design [54].

These types are compression, skin stretch and vibrations. To render these stimuli, the sleeve design consisted of six fluidic muscle sheet actuators, two custom soft force sensors, a knit fabric sleeve base, and velcro connectors, see Figure 9. The sleeve was controlled by pneumatic pressure using compressed air and pressure regulators. The PnueSleeve was tested based on 23 feel effects that correspond to different real-world use cases, these effects were grouped into families based on their similar control signals. These families were acceleration, rotation, heartbeat, navigation, phone, waves and special effects. Results show that participants rated most feel effects high for both goodnesses of fit and feel and found the sleeve to be comfortable [54]. No other affective responses like valence and arousal were captured.

In addition, the McKibben sleeve of the University of Twente uses McKibben actuators to convey compression to the forearm [48].

Figure 4: Participant with their arm in the McKibben sleeve [48].

This sleeve was first produced at Linköping University, whereafter the University of Twente received a copy. The McKibben actuators consisted of 13 pneumatic artificial muscles that convert pressurized air to mechanical motion and force. An artificial muscle consisted of an elastic inner tube that was inserted into a braided mesh sleeve made of inextensible threads. A pneumatic system with a pressure regulator controls the airflow of the McKibben actuators where each McKibben can be activated independently. As can be seen in Figure 4, these McKibbens are placed in a sleeve that could be worn at the forearm. A study with this sleeve by Weda et al. [49] found that force had a major effect on the experience of a passive pressure touch. Moreover, the sensory experiences evoked were "comfortable", "not painful", "squeezing" and "soft" and the emotional experiences were "gentle", "comfortable" and "friendly".

Another haptic device is the ThermoCaress [30], this device uses pressure force to create a stroking sensation on the forearm and also thermal stimulation at the same time, see Figure 5.

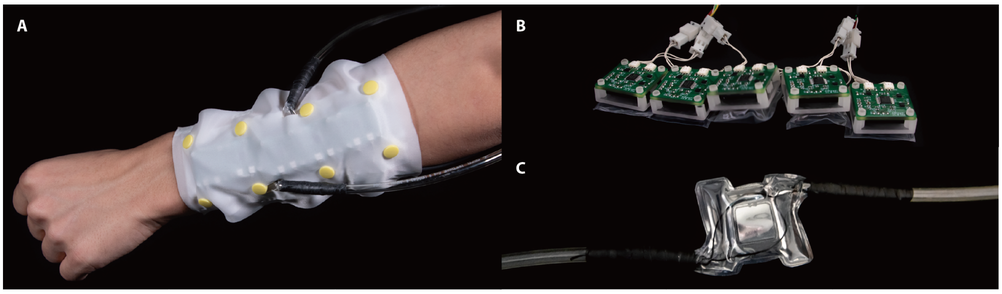

Figure 5: A: ThermoCaress on the forearm, B: Air pressure actuators, C: Water pouch actuator [30].

This device uses a pneumatic system that can be activated by air or water, with the added benefit of water for giving thermal sensations to the user. Furthermore, illusory movement is used to create a stroking sensation. Results of a user study suggest that this device can successfully produce stroking and thermal sensations and that especially cold temperatures were experienced as more pleasant.

Moreover, in the study by Price et al. [39] they presented a prototype of a remote touch device for the hand and underarm, see Figure 6. This device can act as both receiver and sender where the sender can send remote tactile messages to the receiver that vary in temperature, vibration and pressure cues.

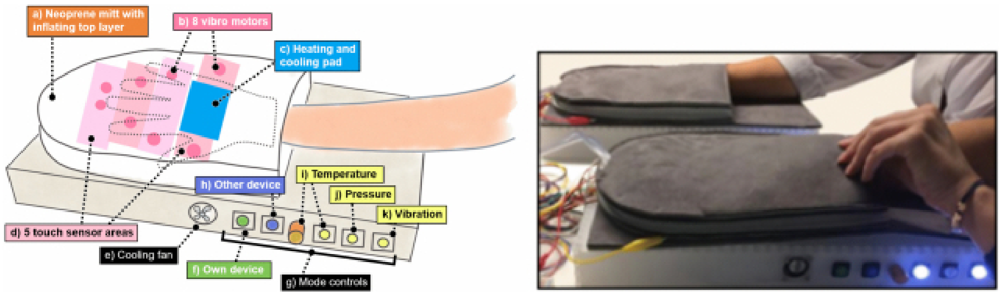

Figure 6: Prototype design on the left and on the right a participant exploring the device, that can act as both receiver and sender [39].

The pressure sensation was generated by using a 12-inch latex balloon that deflates and inflates with air. An exploratory study was performed to explore how meaning is generated around tactile communication and how different modalities could create remote touch exchanges. Results showed that participants could send and interpret messages despite the complex system and scenarios.

In addition, the PnueMod of Zhang and Sra [53], is a modular haptic device that can convey tactile force and thermal sensations. Here pneumatic and thermal actuation was used to deliver pressure and temperature sensations to the user.

Figure 7: Multiple use cases of the PnueMod [53]. a) Sleeve worn on the forearm and d) on the lower leg. h) An actuator attached to a band that can be worn like in e).

Whereby the PnueMod consisted of three main components: a set of silicone thermal-pneumatic actuators, a control system and a flexible wrapping sleeve that can wrap around the forearm or lower leg. Possible applications for this sleeve are VR or mediated social touch communication, however, no study results were presented yet.

Further, Young et al. [52] presented a pneumatic wristband called the Bellowband, see Figure 8.

Figure 8: Participant wearing the Bellowband [52].

This device consists of eight independent actuators that are manufactured by alternating layers of TPU and glue stacked to two layers. These actuators extend upwards when pressurized with air. Results demonstrated that the wristband can generate forces over 10N around the wrist, but further research is necessary to gather participant responses about how these forces are perceived.

Moreover in the study by Zhu et al. [55] they created an output device to generate the sensation of various social touch gestures and an input device to record and transfer these gestures to the user, see Figure 3.

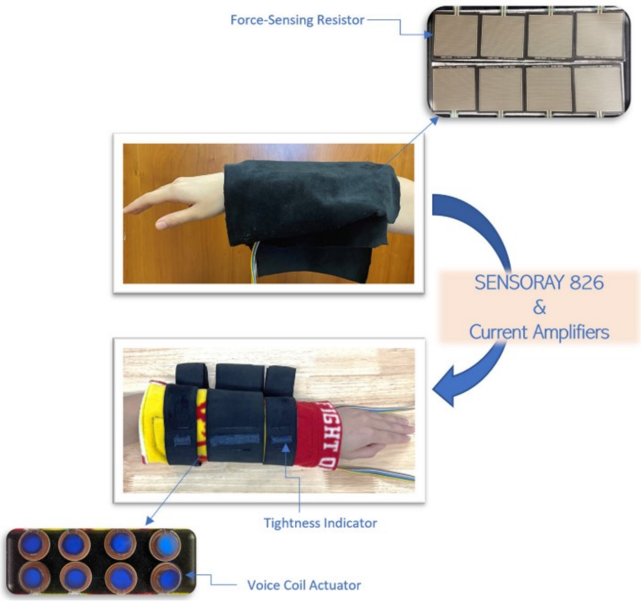

Figure 9: Input device (top) and output device (bottom) design [55].

In the output device, eight-voice coil actuators (Tectronic Elements TEAX19C01-8) were placed in a 4 x 2 array to generate five social touch gestures: poking, patting, massaging, squeezing and stroking. In an experiment using this device, Zhu et al. [55] examined how users interpret the emotion of these mediated social touch gestures and explored the emotional effect of the speed of the gesture. The emotional response was measured using the EmojiGrid to rate their perceived valance and arousal of each touch gesture. Thereafter the system's performance was measured based on realism and comfort using a 7-point Likert scale. Results indicate that speed increases the perceived arousal and decreases its valance. Furthermore, the perception of comfort increased as the speed of the gestures decreased. At last, the emotions the device evoked can be found in Table 1.

Table 1: Table representing the emotional responses of various gestures with different speeds [55].

Emotion	**Gesture**	**Speed**
Anger	Massaging, patting and stroking	Fast
Annoyance	Massaging, patting and stroking	Fast
Amused	Massaging, patting and stroking	Slow
Glad	Massaging, patting and stroking	Slow
Pleased	Massaging, patting and stroking	Slow
Relax	Squeezing	Slow/Medium
Calm	Squeezing	Slow/Medium
Raising attention	Poking	Fast

3.2 Haptic devices that combine touch and texture

Sato et al. [41] designed a prototype of a robot to study affective expression using multiple textures and movements. The robot, see Figure 10, is a rotary wheel where various materials can be attached to its surface. Materials used in the study were plastic resin, aluminium, clay, velcro and cotton.

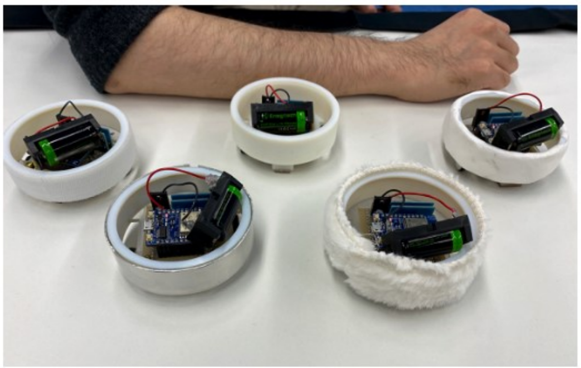

Figure 10: Prototypes of affective touch robots with different textures and materials [41].

The robot was able to do four different movement patterns, namely, tap rapidly (1Hz) and slowly (0.25Hz), stroke rapidly (1Hz) and slowly (0.5Hz). In the experiments, the robot stroked or tapped the forearm of participants with these various materials. Participants were asked to label the interaction by picking one or two emotions from the nine emotions: excited, happy, content, calm, sleepy, bored, sad, afraid, and angry. Results indicated that cold texture mapped to negative valance expression, and rapid movements mapped to excitement, thus high arousal. In conclusion, the frequency of the movement could change the expression of emotional arousal. They argued that it should be possible with this method to cover the spectrum of both valance and arousal through the use of various movements and various textures [41].

Lastly, the EmoBand of Yang and Zhu [50] is a haptic device where different fabric materials can squeeze and stroke the wearer's wrist, see Figure 11.

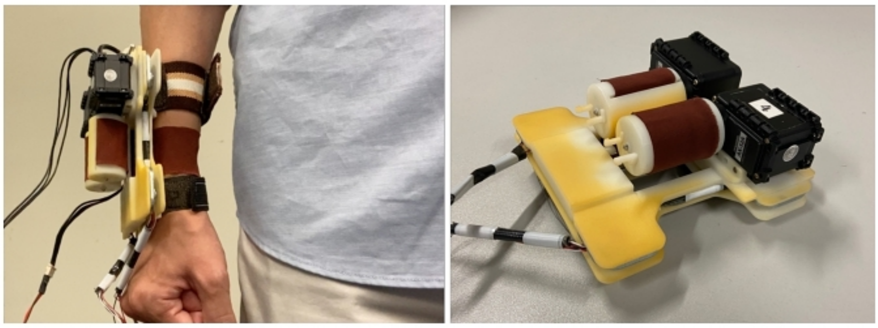

Figure 11: The EmoBand haptic device.

Two servo motor actuators were used to rotate two cylinders with a piece of fabric between them. By rotating the servo motors a stroking or squeezing sensation can be simulated. With this setup, they validated five materials based on softness, slipperiness, smoothness and warmth ranging from 1 to 5. These materials were cotton, silk, flax, wool and leather here silk was perceived as the softest and leather as the hardest material. Furthermore, two studies were performed the first about applying different materials for stroking and the other about applying different materials for squeezing on the wrist. Affective response results showed that different materials evoked different emotional experiences. They found that for both simulations silk and fax-like materials evoked more pleasant emotions than wool-like materials. Furthermore leather and cotton evoked more balanced emotional responses compared to the other three.

3.3 Conclusion

This state-of-the-art review has led to some interesting insights. Firstly, of all studies, only two haptic devices combined touch and texture. This is a very low amount, which makes the combination of texture and haptic devices interesting to explore further. Additionally, no devices were found that used pneumatic activation in combination with texture. Furthermore, most haptic devices that used pressure were only examined on their operations and whether the stimuli were felt. Moreover, the emotions these devices evoked were not studied, but it is interesting to explore before using these devices for mediated social touch. Finally, pressure devices mostly squeeze the user on a particular body part and therefore the most likely emotional responses to be evoked are calming and relaxing emotions [55]. Overall, this review shed light on state-of-the-art haptic devices that used pressure stimuli and or textural stimuli.

4

Methodology

The methodology of this research consists of three studies. The first study examines how a selection of 17 textures are perceived on the forearm. This study will be conducted to validate whether the qualities of soft materials found by Cavdan et al. [8] can be translated to the forearm. Thereby with the results of Study 1, three materials will be selected to use in the third study. In the second study, multiple pressures varying in force and duration will be applied to the forearm. Herefore the participants are asked to complete a survey about their affective response to each stimulus. With this study, data is obtained about the effect of pressure on the forearm causing affective responses. In the third and final study, three textures validated in Study 1, will be used to capture the affective responses of those textures on the forearm. See Figure 12 for a complete overview of the three studies.

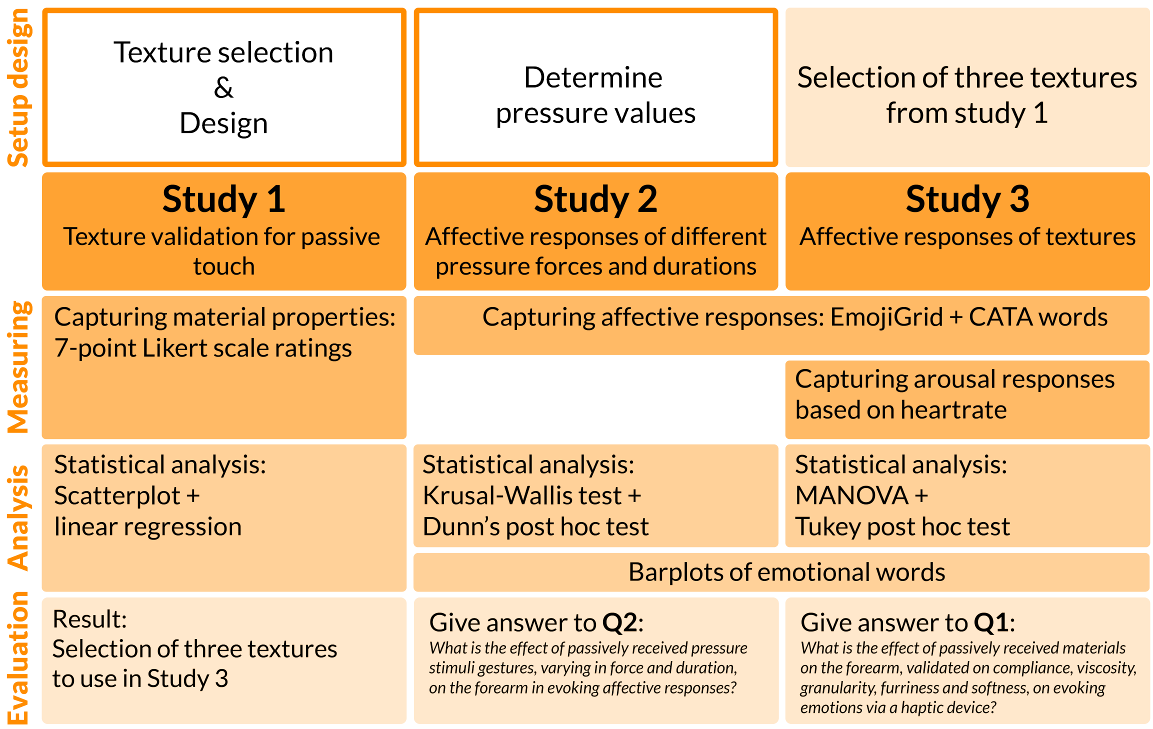

Figure 12: Overview of the studies that have been carried out.

4.1 Research design

To find answers to the research questions this research follows a confirmatory approach. As it is known that textures and pressure touch evoke affective responses, this study will investigate the debated theories about deep pressure [7] and dimensions of soft texture [8]. However, these theories will be tested in a different setting, since passive touch is used contrary to active touch [7] and pressure (through the use of the McKibben sleeve) is used contrary to deep pressure[8]. Therefore, results will be obtained to explore the affective response of texture and pressure to passive touch via haptic devices. Furthermore, qualitative methods will be used to capture the affective responses of human beings, because emotions are subjective experiences. Additionally, the last study has a mixed-method approach by also using a smartwatch that captures heart rate and arousal. With this approach, the obtained subjective data will be compared with the obtained objective data to identify coherence between both data. To perform this research multiple research design decisions have been taken. Hence to address these decisions, the apparatus, setup and data analysis will be discussed. Starting with the apparatus as this device is used in all studies to apply different types of stimuli, followed by the setup where the experiment environment, timeframe, sampling strategy and data collection will be elucidated.

4.1.1 Apparatus

Across all three experiments, the device named McKibben sleeve was used to apply pressure on the forearm. The sleeve had 13 tunnels with McKibben actuators inserted with an average width of 13mm each, see Figure 13.

Figure 13: The McKibbens that were actuated in the studies.

The McKibben actuators have a braided mesh outer sleeve and an elastic inner tube. When pressurized air enters the inner tube it expands and retracts when deflated. The longitudinal stiffness of the braided outer sleeve limits its increase in diameter, causing linear contraction and creating pressure on the arm [49]. Furthermore, the McKibben actuation system was kept the same. Whereby the pressure in the tubes was regulated manually by using a pressure regulator that was placed in between the pressure generator and the pneumatic system. Moreover, the image in Figure 13 highlights the McKibbens that were actuated during the studies. For each stimulus, all eight McKibbens were actuated at the same time. It was decided to activate all eight McKibbens, as textures had to be placed in the sleeve and actuating a large area made the most contact with the texture and the arm. Lastly, the actuation speed of the muscles was almost instantly and only in the second study the pressure and duration of the McKibben muscle contraction were varied.

4.1.2 Setup

The setup across all studies was kept the same, this included a screen and headphones playing white noise to prevent the participant from visual and auditory influences. Consequently, the studies took place in a controlled environment to make it easier to replicate the studies and to deal with fewer variables. For consistency, always participant's left arm was used in the sleeve and placed on top of two cushions. In front of the participant stood a computer that displayed a survey to be filled out with a computer mouse, see Figure 14 for the complete setup.

Figure 14: This setup was used in all studies.

It was chosen to do a cross-sectional study to collect data from a sample of people each time an experiment is performed. Contrarily to a longitudinal study, where the same people will be investigated over time, as this would take a lot of time which is out of this scope. Moreover, the added benefits of performing a longitudinal study by using this device are minimal since it is more of a research tool and not a developed product. Convenience sampling was used for participant recruitment because three studies had to be performed in a small time frame. Resulting in a sample of mainly friends and students and employees of the University. Hereby the sample size was more important than the population diversity. However, demographic information on age and sex was captured to make claims about the generalizability of the data. For statistical power reasons, the sample size for studies 1 and 2 had to be a minimum of 20 participants and for study 3 of 25 participants. All data collection was done via surveys that had to be filled out after the application of a stimulus. The survey for study 1 consisted of five 7-point Likert questions to capture ratings for the material properties of each material. Because of this numerical data was captured that could easily be displayed and analysed. For studies 2 and 3 a Check-All-That-Applies list consisting of emotional words and an EmojiGrid will be used to capture the affective responses of the stimuli. This CATA list consists of 25 emotional words to capture the emotional response of a stimulus in words. This list was defined based on previous studies by Guest et al. [18], Weda et al. [49] which resulted in the following CATA-list: Aggressive, Annoying, Arousing, Calming, Comfortable, Comforting, Delicate, Endearment, Exciting, Frightening, Gentle, Happy, Human, Indifferent, Irritating, Loving, Pleasurable, Sensual, Shocking, Supportive, Surprising, Thrilling, Unpleasant, Uplifting, Upset. Hereof the words: annoying, arousing, calming, comfortable, exciting, gentle, irritating, pleasurable, sensual and thrilling shared in both studies [18, 49], but the rest excluding the word "indifferent" were all in the list defined by Weda et al. [49]. It was important for the list to cover a broad range of words, like positive and negative extreme ones such as "exciting", "aggressive", "and "frightening" and more neutral ones like "calming", "comfortable" and "annoying". The word "indifferent" was selected to be included to give the participant an option in case the stimulus did not evoke any emotion. Furthermore, it was thought that a list of 25 words will be a good amount to show to the participant and also capture a broad range of emotional words. Furthermore, the EmojiGrid of Toet and van Erp [43] see Figure 15, displays valance and arousal in one picture by using emojis, instead of numbers. The outer edge of the grid is labelled with five emotions, with one emotion located in the centre. The emoji located at the centre represents neutral, the horizontal axis valence (increasing from left to right) and the vertical axis represents arousal (increasing from bottom to top).

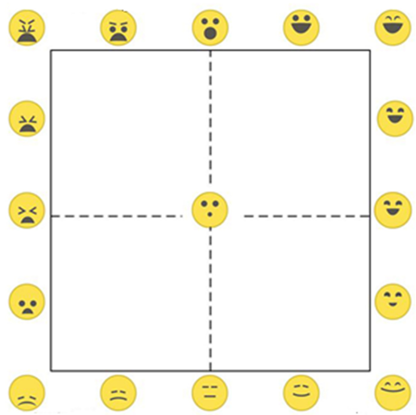

Figure 15: Emojigrid developed by Toet and van Erp [43], with arousal on the y-axis and valence on the x-axis.

Most often the affective dimensions of valence and arousal are used to measure affective responses evoked by tactile stimuli. For this SAM (Self-Assessment Mannkin [6]) scale or Likert scale are frequently used assessment methods. However, according to Toet and van Erp [43] the arousal ratings of the SAM scale are frequently misinterpreted and tend to copy their valence response to the arousal scale. Thereby a drawback of using Likert scales is that participants have to translate their emotions to numbers or labels on a scale. This requires cognitive effort and is less intuitive. With this grid, participants can report their affective state by marking their appropriate location in the grid. Toet and van Erp [43] claims that the EmojiGrid is a valid instrument to report affective states perceived by social touch events and in comparison to the SAM, the EmojiGrid is more sensitive to variations in arousal. Besides the EmojiGrid, a list of emotional words had been added so participants had to verbalize their emotions as well. Using both techniques made it possible to capture the emotions a certain stimulus evokes. Additionally, for the third study, a smartwatch is used to capture qualitative data per participant. This data consisted of heart rate in beats per minute that was captured every second and arousal values that were calculated based on participants' measured heart rate and their baseline measurement. These arousal values ranged from -3 to 5 and only a value was obtained if there is an observed change in arousal. With this mixed-method approach, participants' subjective ratings will be compared with quantitative data to make stronger claims.

4.1.3 Data analysis techniques

The data obtained from Study 1 will be displayed in scatterplots per material as ratings were given for the five qualities: compliance, granularity, viscosity, furriness and softness. Moreover, scatterplots per quality will be displayed, since the goal is to find materials that stand out from the other materials. For example, finding a material that scores only high on viscosity and softness could indicate a relationship between these qualities and thereafter investigate if a certain quality evokes a certain emotion. Scatterplots will be used over other data plot techniques as this technique is good at showing whether the distributions are for example concentrated, normal or skewed, have outliers etc. Moreover, with scatterplots all important data will be displayed as each point represents one rating of a participant on a certain property for a material. Furthermore, passively exploring 16 different textures and rating them on their qualities will make it possible to investigate the relationships between these qualities. These relationships will be analysed by making regression plots for all possible combinations of textural qualities, say for example, softness and roughness. These relationships will thereafter be compared to previous literature on both passive and active touch. To find similarities, limitations or maybe new discoveries between this and other studies. For studies 2 and 3 descriptive statistics of mean, median, variance, standard deviation, minimum and maximum, quartile 1 and quartile 3 will be shown. With this information, the different stimuli can be compared with each other. To extract the affect scores of both studies, statistical models will be used that compare the means of the different stimuli. Herewith the scores for valence and arousal for each stimulus will be compared within the study to find significant results to make substantiated claims. Whereafter these results will be compared with previous literature. The selected emotional words per stimuli will be displayed in frequency plots. This makes it possible to visually interpret how often a certain stimulus evokes a certain emotion. Before analysing the data, the data will be prepared for analysis, this involves matching randomized data with the correct stimulus per participant and cleaning the collected survey data. Whereby data obtained from the EmojiGrid will be transformed from x and y location values back to valence and arousal Likert scores.

4.1.4 Method design limitations

This methodology had some design limitations as some trade-offs had to be made. To start with, due to time constraints, the sample size is low and a possible sample bias occurred that may negatively impact representativeness. Due to convenience sampling, generally, students participated in the studies and therefore the average age of the largest population group is between 20 and 30 years. Moreover, since this is a master's thesis and a total of three studies had to be carried out in a short amount of time, every participant counted. Furthermore, as this study asked for participants' subjective rating demographics may have influenced these responses. The study took place in a controlled environment where external influences were kept to a minimum. A benefit of this was that the experiment was the same for each participant and could therefore be directly compared. However, a downside to this is that the studies can not be translated to a natural environment where also oral, visual and context play an important role in the affective response of touch.

4.2 Concluding Summary

A confirmatory approach based on past research about pressure and soft textures will be used to explore their affective response using a haptic device. Three studies will be carried out to firstly validate different textures for passive touch, whereafter the affective response of different pressures will be explored and lastly the affective response of three validated soft textures will be explored. Across all studies, the same setup and apparatus (McKibben sleeve) will be used. Participants' qualitative data will be captured by filling out a survey during the experiment. Whereafter data analysis techniques scatter plots and regression will be used to validate the textures and statistical models to make claims about valence and arousal responses in combination with frequency analysis of evoked emotional words. Due to time constraints, recruitment is done via convenience sampling and to limitate external influences the study takes place in a controlled environment. By conducting these three studies, the proposed research questions will be answered and the results will be compared to past literature.

5

Setup Design

In this chapter, the setup design of the studies is discussed. Starting with a selection of textures for the apparatus, followed by the design of the textural stimuli, where a 3D printing technique and an incision technique were used. Thereafter values for force and duration to determine the pressure stimuli will be discussed.

5.1 Selection of textures for the apparatus

Figure 16: The first selection of textures

To arrive at the set of textures, inspiration was taken from the studies by Cavdan et al. [8], Dövencioğlu et al. [12]. In these studies, active touch was used to validate the dimensions of compliance, viscosity, granularity, and furriness. To cover a wide range of textures, for each category 4 textures were selected that fit these characteristics, see Figure 16 for all textures. Cavdan et al. [8] extracted the five dimensions based on materials that loaded high on certain adjectives. For the dimension furriness, those adjectives were fluffy, hairy, soft and velvety. Hence fabric materials were selected for this category as most fabrics feature these adjectives. Those fabrics vary mainly in the hair length of the fabric whereof Fur had the longest hairs, followed by Polar, Modal and Velvet. The viscosity category was characterised by the adjectives moist, sticky and wobbly. Herefore the materials Slime represents a sticky material and Humid-Cleaning Wipes a moist material. Moreover, the material Latex was also selected as it was also used in the study by [18] and is a wobbly material. Contrarily, Aluminium foil was selected as a more neutral material and as a counterpart to wet and sticky. Additionally, the adjectives that characterised the dimension granularity were sandy, granular and powdery. Representing materials, therefore, were different types of Sandpaper and Hessian, where Organza was selected as a counterpart because of the absence of any unevenness. Lastly, the dimension compliance featured the adjectives compressible, soft, flexible and elastic. Hence two thicknesses of Leather were selected: 2mm and 4mm, to investigate if thicker materials felt more compressible. Additionally, Bubble wrap was selected as this is a compressible but also granular material due to its relief of multiple bubble particles. At last, a rubber mesh was selected as this was a compressible material and even more flexible because of its mesh characteristics. To cover a wide range, some counterparts, thus textures that scored low on certain adjectives were also selected coming to a total of 16 textures to implement in the apparatus.

5.2 Designing textural stimuli

The McKibben sleeve will be used as apparatus to apply pressure stimuli in all studies. However, after exploring different textures in the sleeve, it turned out that the contraction of the McKibben's could not be felt when using sandpaper and leather-like materials. This is due to the fact that those materials are too stiff to use in the sleeve. Solutions are found to either mimic the material or make the material less stiff. Both techniques are discussed below, where 3D printing is used to mimic a material and incision a material to make it less stiff.

5.2.1 3D printing on textile

A way to create flexible materials is by 3d printing on textiles. A requirement for this was that the textured particles were not too large and there was space between them. In order to find the most expressive texture a texture exploration was performed. The goal of this exploration was to create a granular material that mimics sandpaper. SolidWorks was used to design textures that are fit for 3D printing. This program has multiple built-in texture patterns, hereof the following 16 textures were explored, see Figure 17 with corresponding Table 2 for the used parameters.

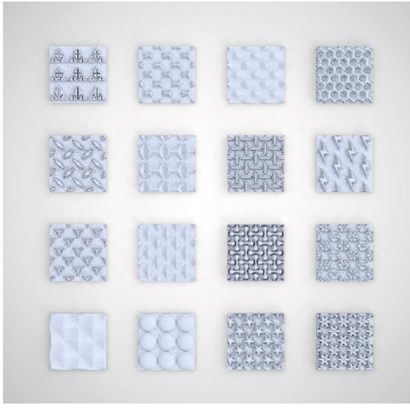

Figure 17: SolidWorks render of multiple textures designed for exploration.

Table 2: This table shows the used texture patterns. The top left texture pattern corresponds with the top left textured particle of Figure 17. In addition, the used parameters to create these particles are displayed.

Texture patterns			
Knurled Bump	Bow Tie Pattern	Bow Tie	Checkered knurl pattern
Bubble	Cone Pattern	Dog Bone Pattern 2	5-point star Pattern
Flower Pattern	Gear Face Pattern	Flash Pattern	3-point star Pattern
Diamond thread Bump	Triangle	Treadplate Bump	Honeycomb
Parameters (per texture pattern)			
Texture Height	1 mm		
Texture Dimensions	17.5 x 17.5 mm		
Distance between textures	10 mm		
Texture Refinement	5.0%		
Texture Offset Distance	1.00 mm		
Maximum Element size	0.75 mm		

The filament PLA (PolyLactic Acid) is used as filament for the 3D prints. After fabrication, all patterns were explored by self-touching them by hand. Out of all 16 textures, the three-pointed star pattern felt the pointiest and sharpest. Furthermore, the ratio between the distance and dimensions of the tiles in the multiple texture 3D print was a little too large to properly fit around the forearm. Thereby the dimensions were adjusted to fit into the sleeve. For the final pattern, the three-pointed star with tile dimensions of 8.0 x 8.0 mm and a distance between the tiles of 4.0 mm was used, see Figure 20.

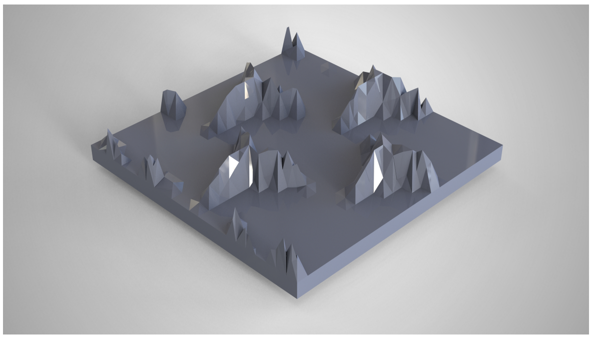

Figure 18: Render of one tile of the three-pointed star pattern, with dimensions: 8.0 x 8.0 mm.

To print on a textile, the textile must have small holes in order for the print to stay attached to the textile. As a result, a textile mesh called Tulle is used, see Figure 19. There were different types of Tulle and this mainly affects how flexible the 3D-printed result will be. The chosen Tulle is a very light and flexible material, this will allow the 3D-printed tiles to move as freely as possible so that it does not absorb the contraction of the sleeve. After one layer of filament, the mesh was placed on top of the layer and attached to the bed, whereafter the print continued. See Figure 21 for the final result.

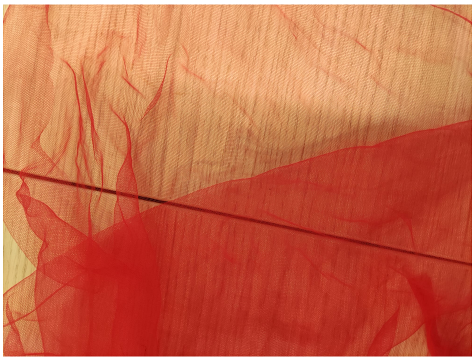

Figure 19: This textile mesh, called Tulle, was used for 3D-printing on textile.

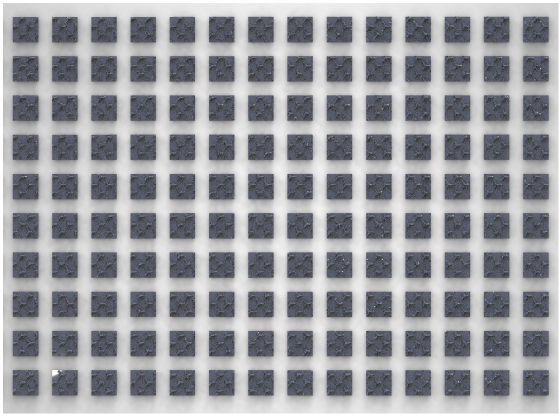

Figure 20: Render of the three-pointed star pattern, with dimensions 120 x 180 mm.

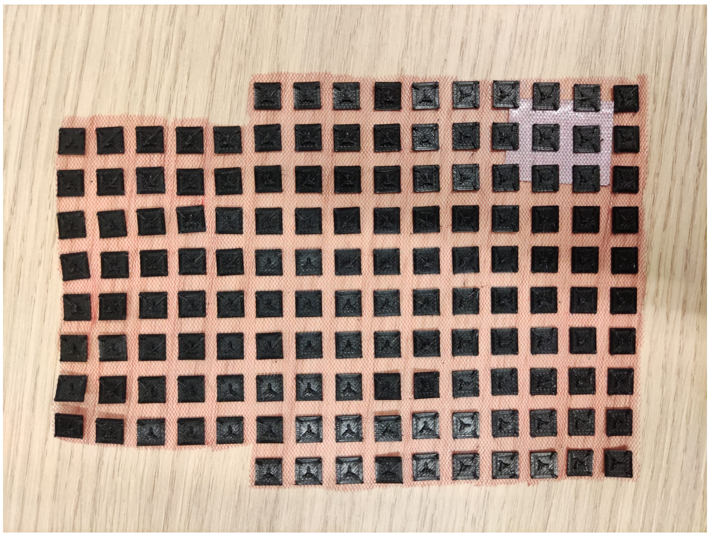

Figure 21: 3D print with filament PLA on Tulle and made to fit the sleeve.

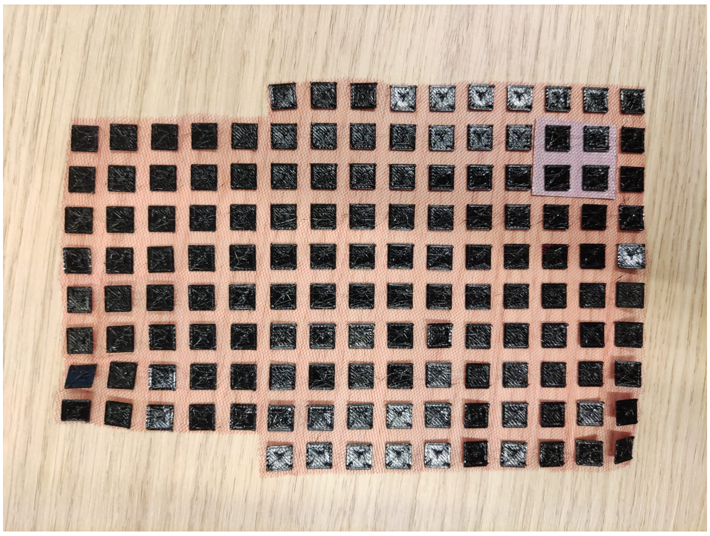

Figure 22: 3D print with filament TPU on Tulle.

The texture of Figure 21 was made with a hard plastic PLA filament. For a second 3D printed texture a more flexible filament was used, that of TPU (Thermoplastic Polyurethane). All parameters like dimension, pattern and textile material (tulle) were kept the same. This resulted in the 3D print of Figure 22. A more flexible TPU filament was used to find out what the effect of a more flexible material is while keeping all other parameters the same.

5.2.2 Incising materials

Another way to make textures more flexible was by incision. By making small incisions using the right template at the right places the material will still be intact, but become way more flexible. See Figure 23 for an example of the used template.

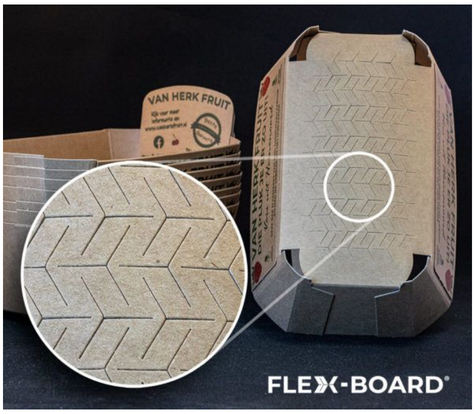

Figure 23: An incision pattern called Flex-Board to make carton board flexible [17].

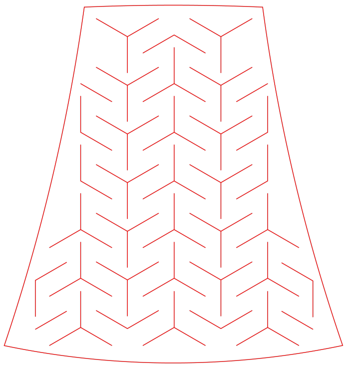

Figure 24: Laser cut template.

Inspiration was taken from the cardboard called Flex-Board [17], see Figure 23, to create a template for the laser cutter, see Figure 24. The leather materials were laser cut in the shape of the template, resulting in the texture of Figure 25. Furthermore, the template was also used to laser cut a 4mm thick leather texture.

Figure 25: 2mm Thick pork leather after laser cutting it with the template.

5.3 Determining the pressure stimuli

When humans interact with each other through touch emotions will be evoked. In haptics, the way someone touches another to convey meaning or intent is called a touch gesture. Yohanan and MacLean [51] defined a touch gesture as follows: "the placement of a part or parts of one's body in direct physical contact with another's body, often coupled with movement, in order to convey meaning or intent." In this study, the way of making physical contact with the arm by applying pressure will be researched. Jung et al. [28] presented a list of touch gestures, see Figure 26, that were applied to the arm.

Gesture label	Gesture definition
Grab	Grasp or seize the arm suddenly and roughly
Hit	Deliver a forcible blow to the arm with either a closed fist or the side or back of your hand
Massage	Rub or knead the arm with your hands
Pat	Gently and quickly touch the arm with the flat of your hand
Pinch	Tightly and sharply grip the arm between your fingers and thumb
Poke	Jab or prod the arm with your finger
Press	Exert a steady force on the arm with your flattened fingers or hand
Rub	Move your hand repeatedly back and forth on the arm with firm pressure
Scratch	Rub the arm with your fingernails
Slap	Quickly and sharply strike the arm with your open hand
Squeeze	Firmly press the arm between your fingers or both hands
Stroke	Move your hand with gentle pressure over arm, often repeatedly
Tap	Strike the arm with a quick light blow or blows using one or more fingers
Tickle	Touch the arm with light finger movements

Figure 26: Touch dictionary of Jung et al. [28], adapted from Yohanan and MacLean [51]

Out of the gestures presented in Figure 26, hereof only the ones where pressure was passively applied to the arm were of interest in this research. Further narrowing, Bianchini et al. [5] proposed only four gesture definitions, as this combination was broad enough to cover all relevant gestures of Alonso-Martin et al. [1], Jung et al. [28], Silvera Tawil et al. [42], Yohanan and MacLean [51]. Bianchini et al. [5] defined the following gesture categories:

1. *Tap Gesture*: A tap is an impulse-like event, wherein the contact is made and broken in quick succession.

2. *Touch Gesture*: A touch is analogous to a tap with indefinitely longer duration

3. *Grab Gesture*: A grab was defined as more than one touch occurring simultaneously in multiple directions.

4. *Slip Gesture*: A slip involves a contact motion and may involve contact from one primary direction or from two directions.

Table 3: Table that compares the touch gestures of study Bianchini et al. [5] with studies: Yohanan and MacLean [51], Jung et al. [28], Silvera Tawil et al. [42] and Alonso-Martin et al. [1] (fLTR)

Bianchini et al. [5]	[51]	[28]	[42]	[1]
Tap	hit, pat, poke, slap, tap	hit, pat, poke, slap, tap	pat, slap, tap	slap, tap
Touch	contact, hold, lift, press, push	press	push	
Grab	cradle, grab, hold, pinch, pull, squeeze	grab, pinch, squeeze		
Slip	rub, scratch, stroke	rub, scratch, stroke	scratch, stroke	stroke
Excluded	finger idly, hug, kiss, massage, nuzzle, pick, rock, shake, swing, tickle, toss, tremble	massage, tickle		tickle

In this research, the slip gesture will not be addressed as it involves contact motion which is out of the scope of this study as only applying pressure on the arm was relevant to this study. The gestures tap, touch, and grab can all be simulated by applying pressure. To determine the duration of the force for the experiment values of touch duration were obtained from the study of Yohanan and MacLean [51]. In this study, a haptic robotic creature with an array of touch sensors over its body, coupled with an accelerometer, was used to record the interaction between a human and this creature. Thereby the applied touch gestures were researched to gather insights into what touch gestures were likely to be used to communicate emotions of Ekman et al. [13], Russell [40]. As a result, a list of 18 different touch gestures that were used to communicate emotions was presented. Hereof three touch gestures were selected, based on the following criteria. The touch gesture could at least communicate five different types of emotions, was easily replicable and each gesture should represent a different type of the definitions tap, touch, and grab [5].

Pat	Aroused	0.47	1.85	Contact	Miserable	5.29	1.69	Hold	Distressed	7.11	2.27
	Excited	0.36	1.76		Neutral	5.24	1.59		Excited	5.63	2.27
	Neutral	0.50	1.65		Pleased	3.72	1.86		Miserable	7.28	2.17
	Pleased	0.51	1.76		Depressed	5.59	1.77		Neutral	7.21	2.27
	Depressed	0.68	2.00		Sleepy	5.24	1.65		Pleased	6.34	2.10
	Sleepy	0.79	1.60		Relaxed	5.83	1.69		Depressed	6.40	2.17
	Relaxed	0.71	1.66						Sleepy	7.90	2.07
									Relaxed	7.36	2.13

Figure 27: Mean duration (first value) and mean pressure intensity (second value) for the gestures pat, contact, and hold (fLTR) [51].

Resulting in the selection of the gestures tap, hold and grab which were easily replicable and covered a wide range of gestures and emotions. Hereof 'Tap' represented the gesture Tap, 'Contact' represented the gesture Touch and 'Hold' represented the gesture Grab. The mean values for duration and pressure intensity (force) to communicate emotions can be seen in Figure 27. Based on this, the values for the duration were defined: Pat has a duration of 0.50 seconds, Touch has a duration of 5.00 seconds, and Grab has a duration of 6.50 seconds.

For all studies, the McKibben sleeve will be used as a haptic device, see Figure 28. This sleeve uses pneumatic activation to activate McKibben muscles that compress around the forearm.

Figure 28: Top view of the McKibben sleeve

The parameters for the force of the pressure were determined based on the limitations of the sleeve. It was found that at a force lower than 0.3 bar, the pressure level could not be adjusted accurately by the pressure regulator. Furthermore, for force levels higher than 0.5 bar the McKibbens and valves were starting to leak air if at least eight McKibbens were actuated at the same time. When following a linear increase, the following three levels were chosen: 0.3 bar, 0.4 bar and 0.5 bar.

5.4 Discussion

This section answers the following subquestions:

SQ1.3.1 How to select or design the material so that its properties and contraction can be well perceived in the apparatus used?

and,

SQ2 What are relevant values for pressure force and duration on the forearm in mediated social touch?

Starting with **SQ1.3.1**, solutions for the limitations of the apparatus were found. One of the limitations was that the contraction of the McKibbbens could not be perceived with stiff textures in the sleeve. To solve this, the designed textures were way more flexible than their original counterparts. While testing them in the sleeve, the contraction could still be felt and the 3D-printed textures mimicked sandpaper and velcro-like material. The leather textures with incisions were far more flexible than before and sleeve contraction was palpable. Furthermore, issues occurred when the force of the pressure stimuli was either too low or too high. Finding a compromise to use pressures of 0.3 bar as the lowest and 0.5 bar as the highest stimuli. Thereby, when contracting a total of ten McKibben muscles at once, the program crashes if the duration of contraction was above 4 seconds. To solve this problem, the number of muscles contracted at the same time was reduced to eight.

The section above gives insights into answering question **SQ2** and determining relevant values for the pressure stimuli. Herefore studies were discussed that use pressure on the arm in mediated social touch. This resulted in the gestures pat, touch and grab for social touch when using pressure on the arm [5]. Thereafter parameters of the durations for these gestures were found in the study by Yohanan and MacLean [51]. These values were 0.5 seconds (pat), 5.0 seconds (touch or contact) and 6.5 seconds (grab or hold). When looking at figure 27, these durations were used to communicate a lot of different emotions which made it interesting to investigate further. In the case of the pressure force, besides the apparatus limitations for force, the minimal force had to be above 0.2 bar to be perceived [49]. Resulting in the values for the pressure stimuli with a duration of 0.5, 5.0 and 6.5 seconds and a force of 0.3, 0.4 and 0.5 bar. The discovered values for pressure force and duration and the designed textures will be used as stimuli for the studies.

6

Study 1

This is the first study out of three in total and contains the study design, the results of the experiment and a discussion about the results. This study is performed to validate and select three textures for the third study where their affective response will be studied. Thereby a total of 16 textures will be validated based on the characteristics of compliance, viscosity, granularity, furriness and softness.

6.1 Study design

This study was performed to find answers to the following research questions:

SQ1 How are the qualities of soft materials (varying in compliance, granularity viscosity and furriness) perceived when passively applied to the forearm?

- **SQ1.1 How do passively applied materials (varying in compliance, granularity, viscosity and furriness) on the forearm relate to softness?**
- **SQ1.2 How do passively applied materials (varying in compliance, granularity, viscosity and furriness) on the forearm relate to each other?**
- **SQ1.3 What are representative and available soft materials that resemble these textural qualities in passive touch?**

Cavdan et al. [8] found these qualities of soft materials in an active touch experiment and therefore can not be translated to passive touch. By freely exploring a material more material characteristics are explored relative to passive touch. Therefore this study will investigate if these qualities of soft materials also translate to passive touch. The goal of this study is to make a selection of three textures to use in Study 3 and to validate a set of 16 textures for passive touch. The study design consists of the sections participants, stimulus parameters, procedure, materials, measures and data analysis which are discussed below.

6.1.1 Participants

A total of 21 people participated in this study with an average age of: 27.81 years and sexes: 11 Females (52.4%), 9 Males (42,9%) and 1 I don't want to tell (4.7%). Each session had a total duration of approximately 30 minutes. Convenient sampling was used for the recruitment of participants that had to be above the age of 18 years. To prevent participants from risks, a statement of health form had to be completed to exclude participants that bruise extremely easily, were taking anti-coagulants or had latex-related allergies. In addition, an updated Covid-19 checklist was used to check for symptoms on the day of participation. Participants were excluded if they did not meet the conditions.

6.1.2 Stimulus parameters

In each set-up, four stimulus parameters of soft texture were varied: the compliance of the texture, the viscosity of the texture, the granularity of the texture, and the furriness of the texture, all with four levels each. All textures were applied in random order, excluding the first stimulus which was always the sleeve without texture. A total of seventeen textures were exposed one time to the participant. The force and duration of the pressure were kept constant, with a duration of 5.00 seconds and a force of around 0.4 bar (40 kPa). The stimuli were applied to the dorsal side of the left arm.

6.1.3 Procedure

Before the start of the experiment, participants were asked to seat at the table in front of a computer screen and asked to sanitize their hands and left arm. Thereafter it was explained what the participant had to do in the experiment and presented a word definition list together with the information brochure. Subsequently, the participant filled out the Covid-19 checklist and statement-of-health form. After completion, the consent form was filled out. Hereafter the participants were asked to place their left arm behind a screen on the opened sleeve. Before starting the experiment it was made sure that the participant was sitting comfortably and that the instructions and explanations were clear. The sleeve covered the under and upper arm and was closed by the executive. To prevent visual and auditory influences, the participant's arm with the sleeve was placed behind a screen and the participant wore headphones playing white noise. At the start of the experiment, the executive adjusted the sleeve to fit the participant's arm. Furthermore, to familiarize the participant with the procedure and give the participant a reference point to relate to, the first stimulus did not contain a texture other than the sleeve. After applying each stimulus the participant filled out a survey about the material properties of the presented material. The survey consisted of five 7-point Likert scale questions, to rate the level of compliance, granularity, viscosity, furriness, and softness of the texture. Herein 1 represented 'strongly disagree' and 7 'strongly agree'. After answering a question, the executive opened the sleeve to replace a texture and closed it to apply the stimulus again, until all sixteen textures were applied. At the end of the experiment, the participant was thanked for participating and answered any questions the participant had, for example, a lot of participants were curious about what the textures looked like.

6.1.4 Materials

A total of 16 materials were obtained, those materials can be found in Figure 29. These materials were selected based on Cavdan et al. [8] four dimensions of softness, for more explanation of why these textures are selected see the previous chapter section *Selection of textures for the apparatus*. For granularity, the designed materials 3D printed PLA and 3D printed TPU were selected. Both textures have granular characteristics since they are pointy and there is space between the particles. However, the particles were still connected since otherwise it was not possible to use them in the sleeve. For compliance both selected leather materials were incised to make them more flexible to be used in the sleeve. Furtheremore, to cover a wide range also textures that scored low on a specific dimension where selected. Overall, for every dimension 4 textures were selected to fit into this dimension and it was tested to be possible to apply a total of 17 textures including the sleeve within a timeframe of 30 minutes.

Table 4: Materials used for the textures. The order of the materials (fltr) in the table was the same as displayed in Figure 29.

Qualities	Materials
Granularity	3D printed PLA, 3D printed TPU, Hessian, Organza
Viscosity	Slime (Bouncing Putty), Latex glove, Aluminum foil, Humid cleaning wipes
Furriness	Fur fabric, Polar fabric, Modal fabric, Velvet fabric
Compliance	Pork leather (2mm), Bubble Wrap, Pork leather (4mm), Rubber (Anti-slip mesh)

Figure 29: Set of all 16 textures used in the study, see Table 4 for the material names.

6.1.5 Measures

To assess participants' perceptions of different material properties, ActivePresenter 8 was used as survey-making tool. The survey consisted of 85 Likert scale questions, each using a

7-point scale ranging from "Strongly Disagree (1)" to "Strongly Agree (7)". Participants were asked to rate each stimulus on the five material properties of compliance, granularity, viscosity, furriness, and softness, see the Appendix Figure 65 for images of the survey. To rate the material property compliance, the words "compliant" and "compressible" were chosen. Thereby other words used to explain this material property could be found on the definition list and were: deformability, squeezability or flexibility with the counter word stiff. The granularity property was described with the words "gritty" and "granular". More definitions from the list were graininess, grittiness or coarseness with fine as the counter word. To rate the material property viscosity, the words "viscose" and "adhesive" were selected. More definitions were adhesiveness, tackiness and viscosity with the counter word non-adhesive. The words "hairy" and "furry" were used to rate the material property furriness. Other definitions presented were hairiness, pile or furriness with the contrary word bald. Finally to rate the softness of a material the word "soft" was used with the contrary word hardness. Overall a survey was made to rate a total of 17 textures on the five material properties.

6.1.6 Data Analysis

The data for this study was collected through a survey that included five Likert scale questions for each stimulus. By accident, the survey allowed for proceeding to the next question after answering only one of the five Likert questions. Unfortunately, this caused some missing values in the data. Three participants had missing data, with two participants missing only one answer and one participant missing seven answers. To prepare the data for analysis, Python 3 was used with three specific modules: Statistics, Sklearn Linear Regression, and Matplotlib. The data that was selected from each participant included age, sex, and a total of 85 answers about the textures. Any special characters were removed and the column headers were renamed to make the data easier to work with. Each stimulus was matched with the randomized ordered list in which the textures were applied. In more detail, per participant, a texture was matched with their corresponding five Likert answers about the material. To create strip plots the data per material was selected to visualize the distribution of responses for each material. For the scatterplots, the mean was calculated for all five material qualities per material. To calculate the mean quality, the mean value was taken out of the 21 responses for each quality. This helped to better understand the relationship between the material property and the responses of the participants. Overall, the data analysis approach allowed for carefully examining the relationship between the textures.

6.2 Results

For each material, strip plots were created per texture quality of softness. For each texture, their Likert scores for the five material properties were displayed as their own scatterplot. Starting with the texture called 'no texture' or in other words the McKibben sleeve.

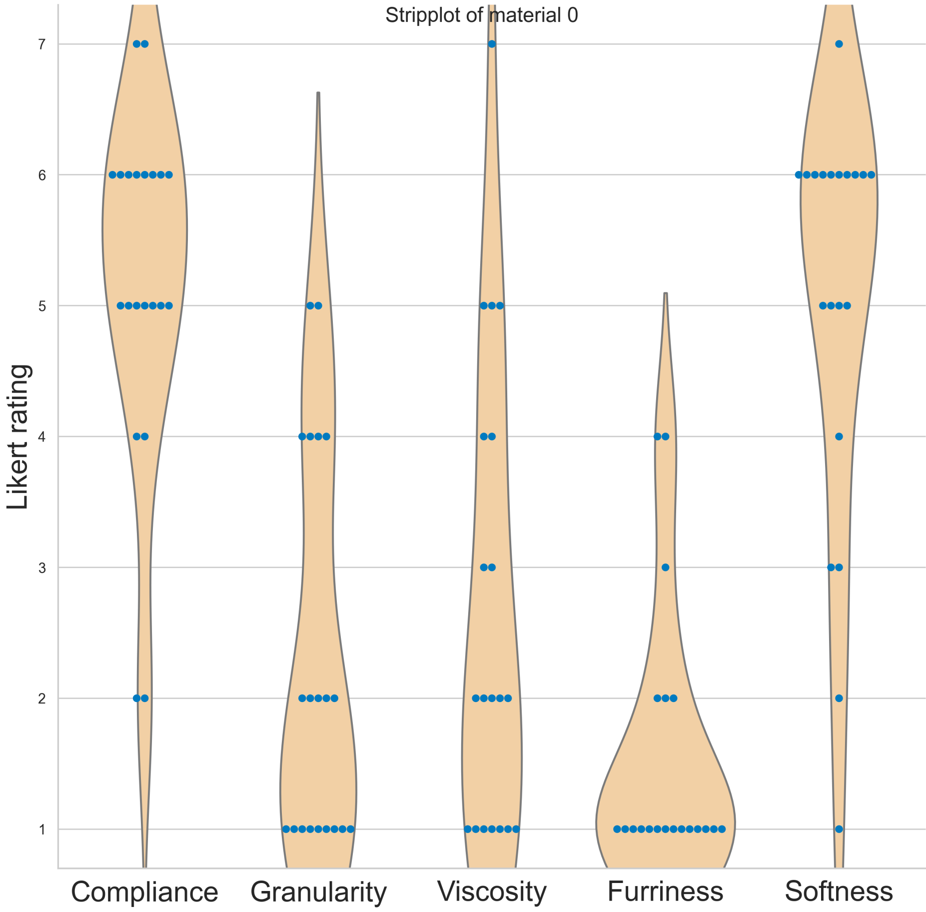

Figure 30: Strip plot of material: Sleeve (no-texture). Each dot represents the rating of a participant on a 7-point Likert scale for the factors: compliance, granularity, viscosity, furriness and softness.

Figure 30 showed strip plot data of the McKibben Sleeve, see Appendix A.1 for all strip plots. The data suggests that the sleeve felt compliant (rating around 5 and 6) and soft (rating around 6). Where the categories granularity, viscosity and furriness scored low for this material.

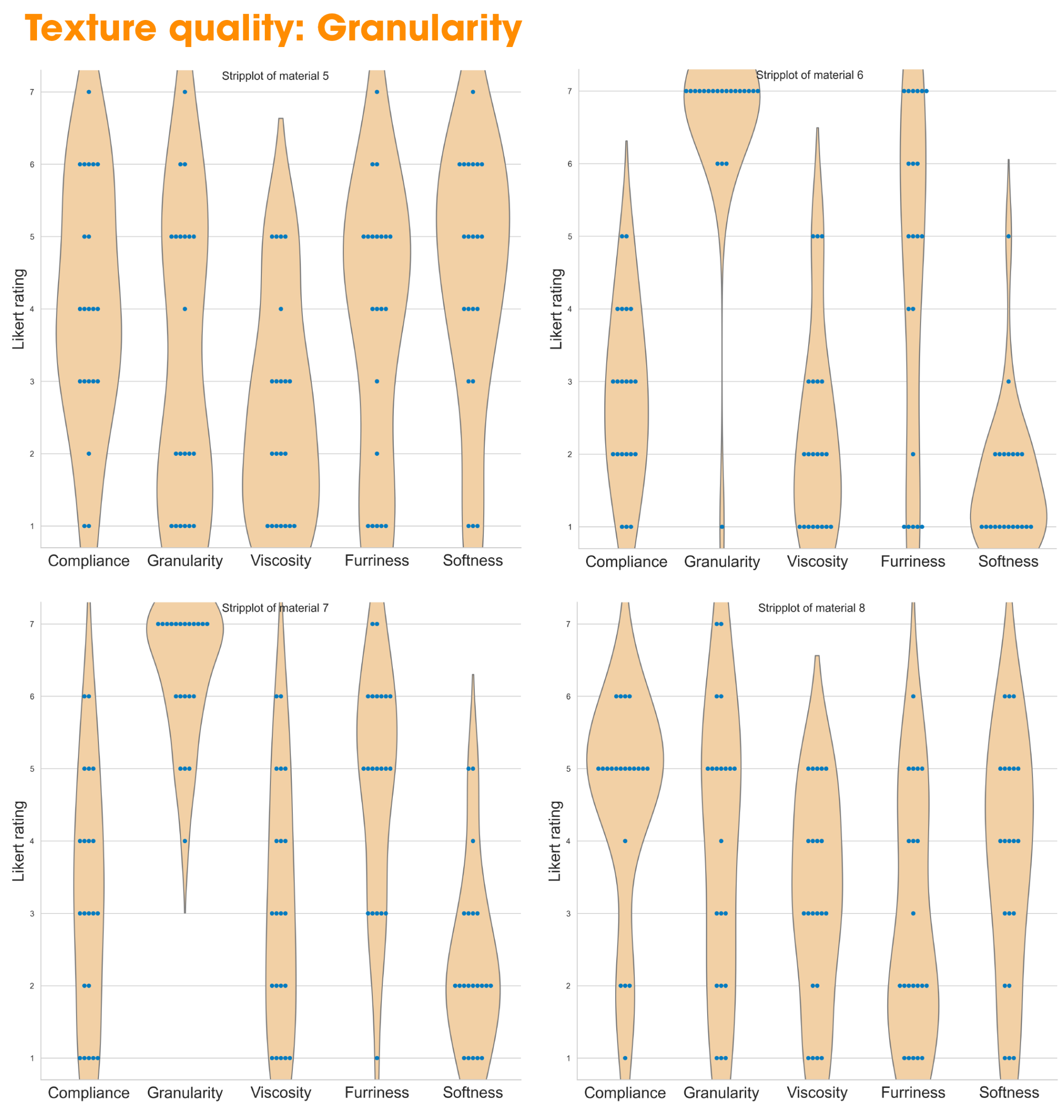

Figure 31: Strip plot of materials selected based on the texture quality of Granularity. Fltr: material 5 = Organza; 6 = 3D Printed PLA; 7 = 3D Printed TPU; 8 = Hessian.

The textures displayed in Figure 31 were selected and designed for the textural quality granularity. Hereof the 3D printed materials scored the highest on granularity, respectively PLA, around 7 and TPU around 7 and some below. Both materials scored low on softness where PLA scored the lowest around 1 and 2, and TPU scored a little higher with a mean of around 2. Thereby the scores for compliance and viscosity were widely spread. Furthermore, for the organza material, the scores for all the categories were widely spread. At last, the hessian material scored around 5 for granularity whereas the scores for the other categories were widely spread.

Texture quality: Viscosity

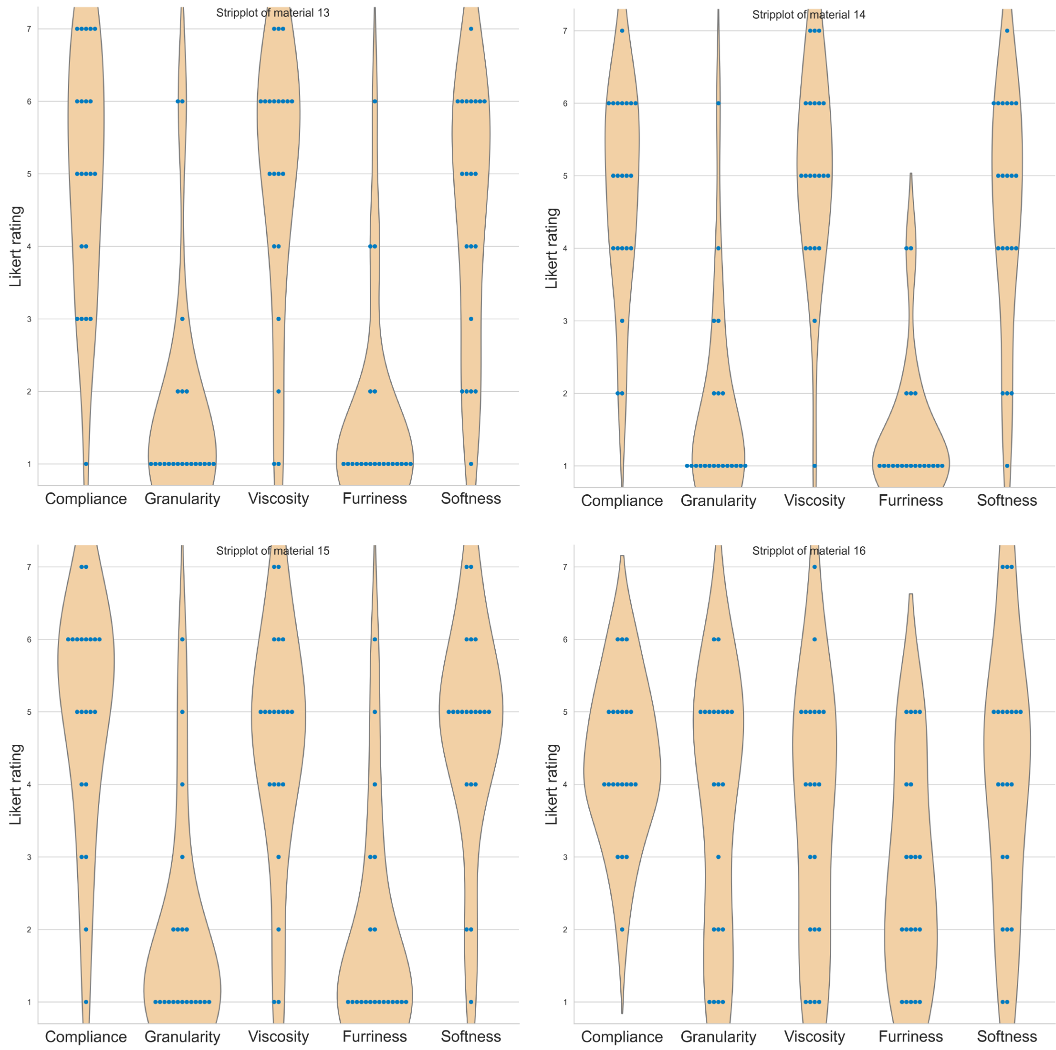

Figure 32: Strip plot of materials selected based on the texture quality of Viscosity. Fltr: material 13 = Slime; 14 = Humid Cleaning Wipes; 15 = Latex Glove; 16 = Aluminium Foil.

Figure 32 showed textures selected for the quality viscosity. Hereof the slime texture scored the highest on viscosity, around 6. The textures slime, humid cleaning wipes and latex glove all scored low on granularity and furriness whereby the scores for compliance were widely spread. Hereof the latex glove scores the most universally on compliance around 5 and 6 and softness around 5. On the other hand, the scores for aluminium foil were widely distributed over all the categories.

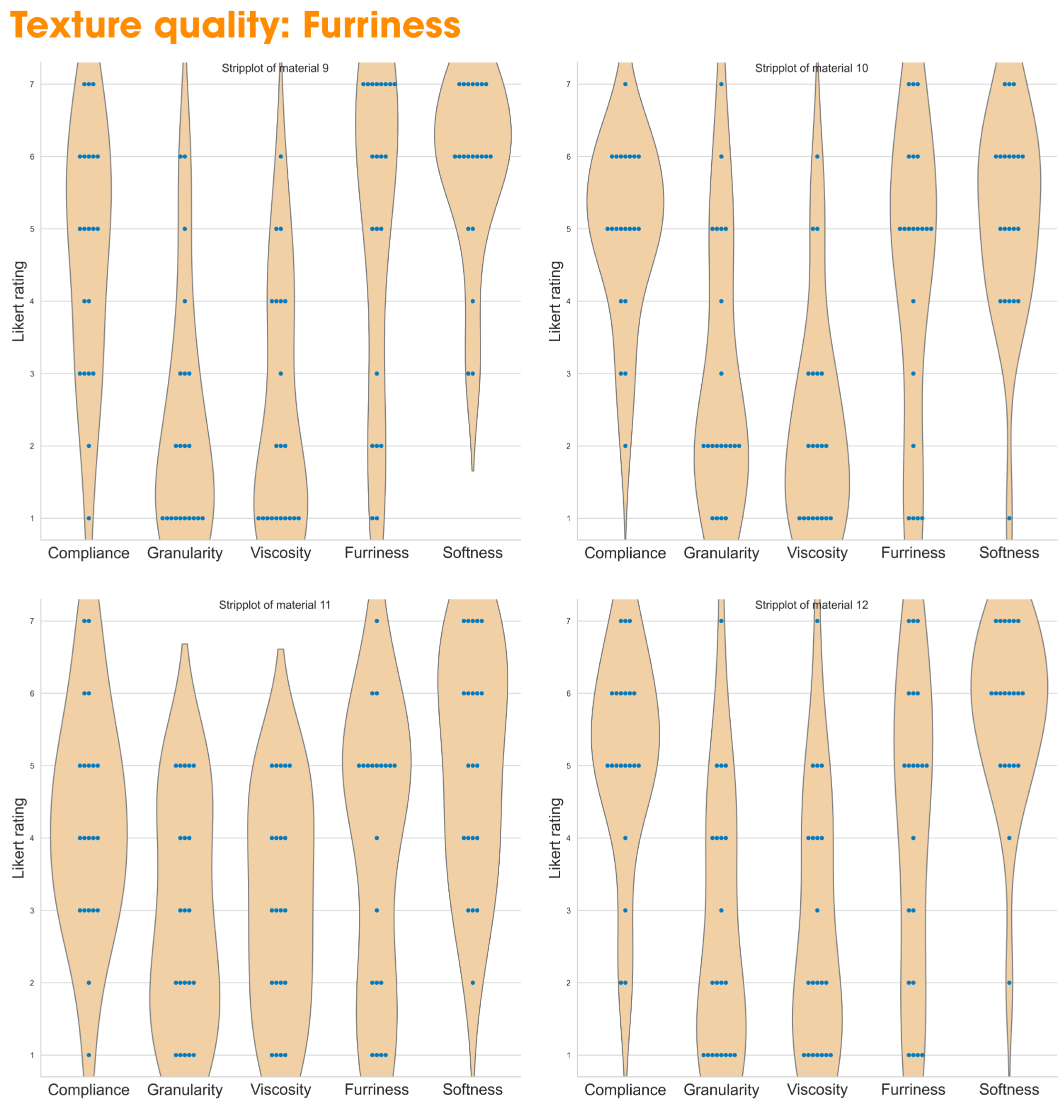

Figure 33: Strip plot of materials selected based on the texture quality of Furriness. Fltr: material 9 = Fur Fabric; 10 = Modal Fabric; 11 = Velvet Fabric; 12 = Polar Fabric.

Figure 33 showed the scores for the textures selected for the quality furriness. From this, the fur fabric scored the highest on furriness, around 7 and softness around 6 and 7, followed by the modal fabric and the velvet fabric. Whereas the fur texture scored low on granularity and viscosity, which is the same for modal. Furthermore, the compliance scores for the fur, modal and velvet textures were widely spread. Whereby the scores for granularity and viscosity for the velvet texture were spread between 1 and 5. The polar fabric scored high on compliance, around 5 and 6 and softness, around 5 and 7, where the scores for furriness were widely spread.

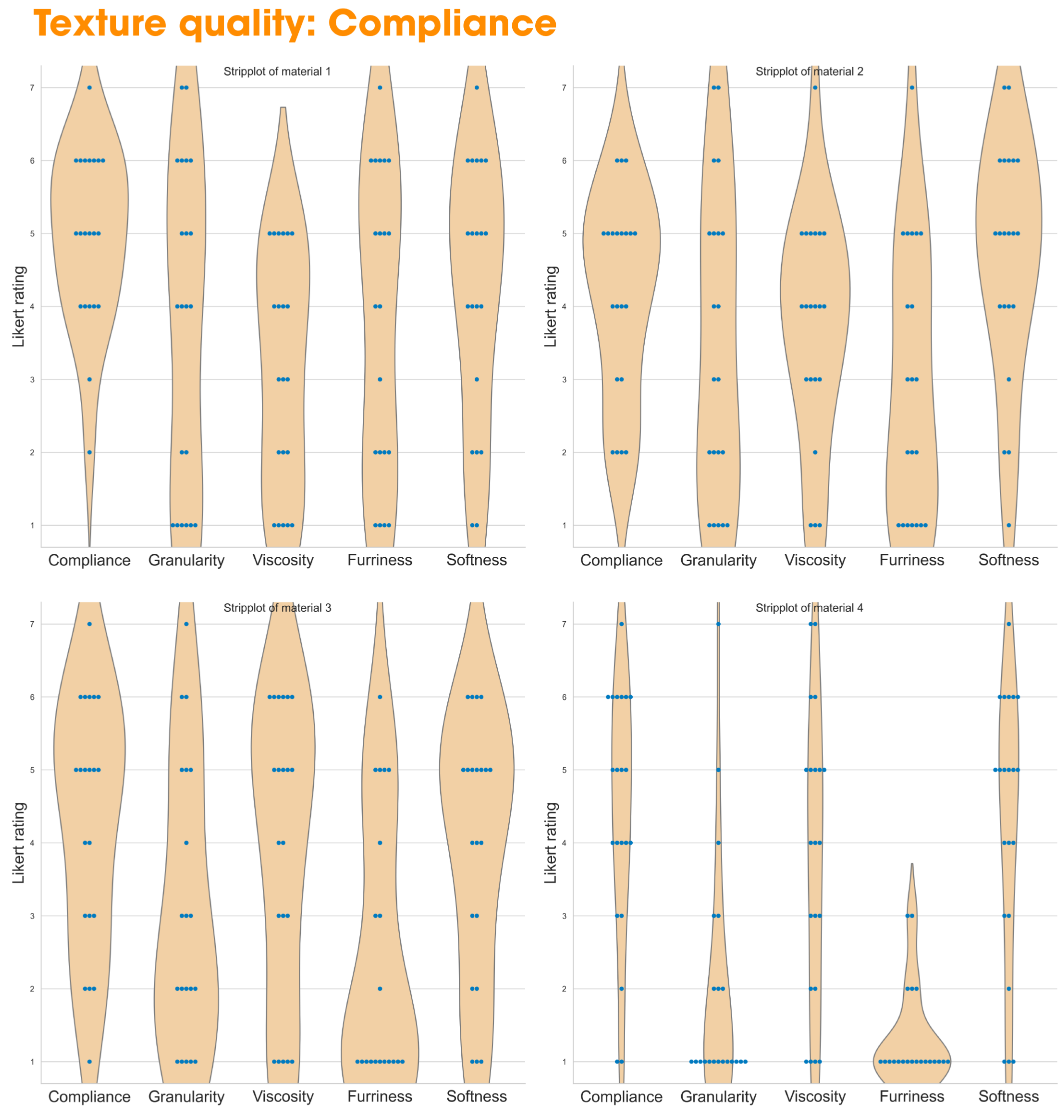

Figure 34: Strip plot of materials selected based on the texture quality of Compliance. Fltr: material 1 = Bubble Foil; 2 = Rubber Mesh; 3 = Pork Leather (4mm); 4 = Pork Leather (2mm).

Strip plot scores for the textures designed and selected for the property compliance can be found in Figure 34. Hereof it is not very clear what texture scored the highest on compliance since all scores were widely spread. The most distinguishing texture was pork leather (2mm) since it scored low on both granularity and softness. Furthermore, the scores for the textures bubble foil and rubber mesh were widely distributed in all categories.

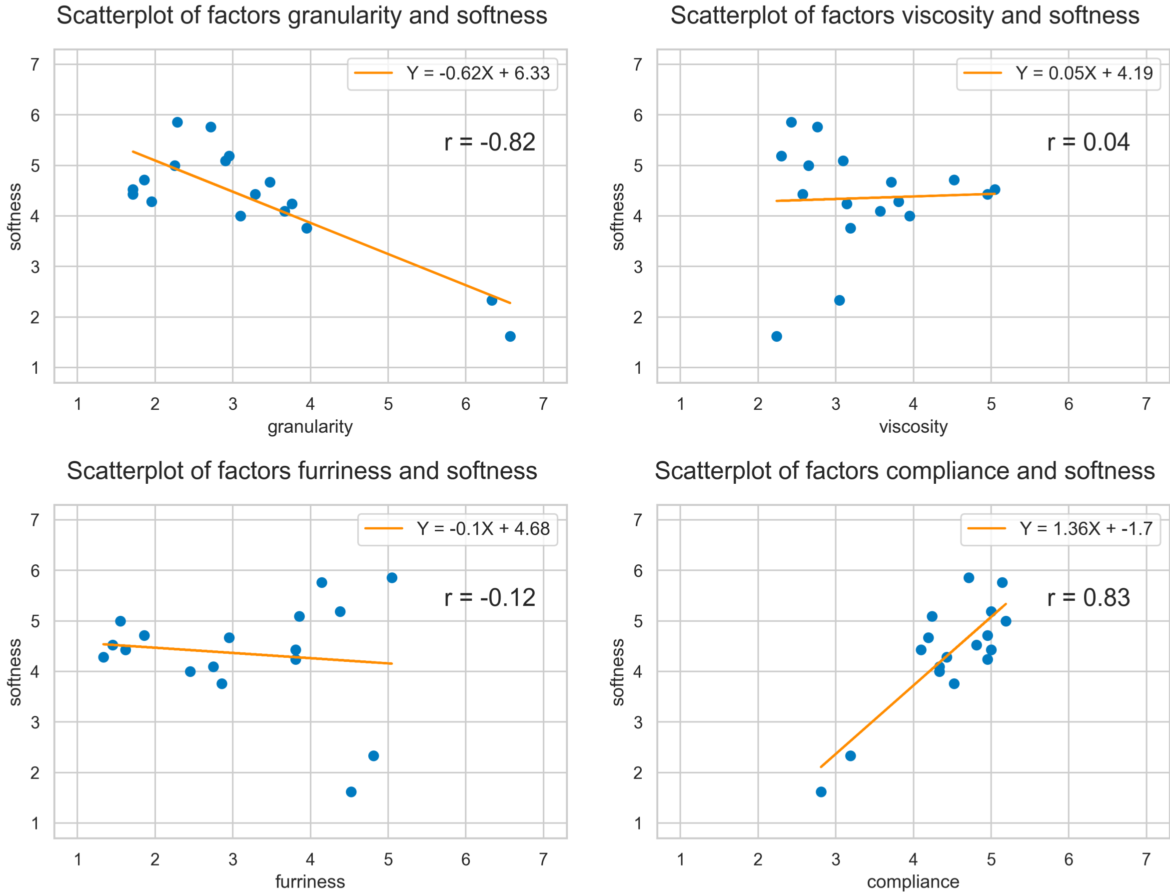

Figure 35: Scatterplots with regression line. With the factors on the x-axis granularity, viscosity, furriness and compliance in relation to softness on the y-axis.

Figure 35 shows the scatterplots with linear regression lines between the average softness rankings and associated dimensions. Each dot represents one of the seventeen textures with its mean score for the quality softness and the four factors: granularity, viscosity, furriness and compliance. The Pearson correlation coefficient r and p-value were calculated to find the linear relationship between the factors. The factors softness and granularity had a strong negative linear correlation $r=-.82$, $p<.01$. Where compliance and softness had a strong positive relationship, $r=.83$, $p<.01$. Finally, there was no indication that there exists a linear correlation between the factors viscosity and softness, $r=.04$, $p>.01$ and furriness and softness, $r=-.12$, $p>.01$.

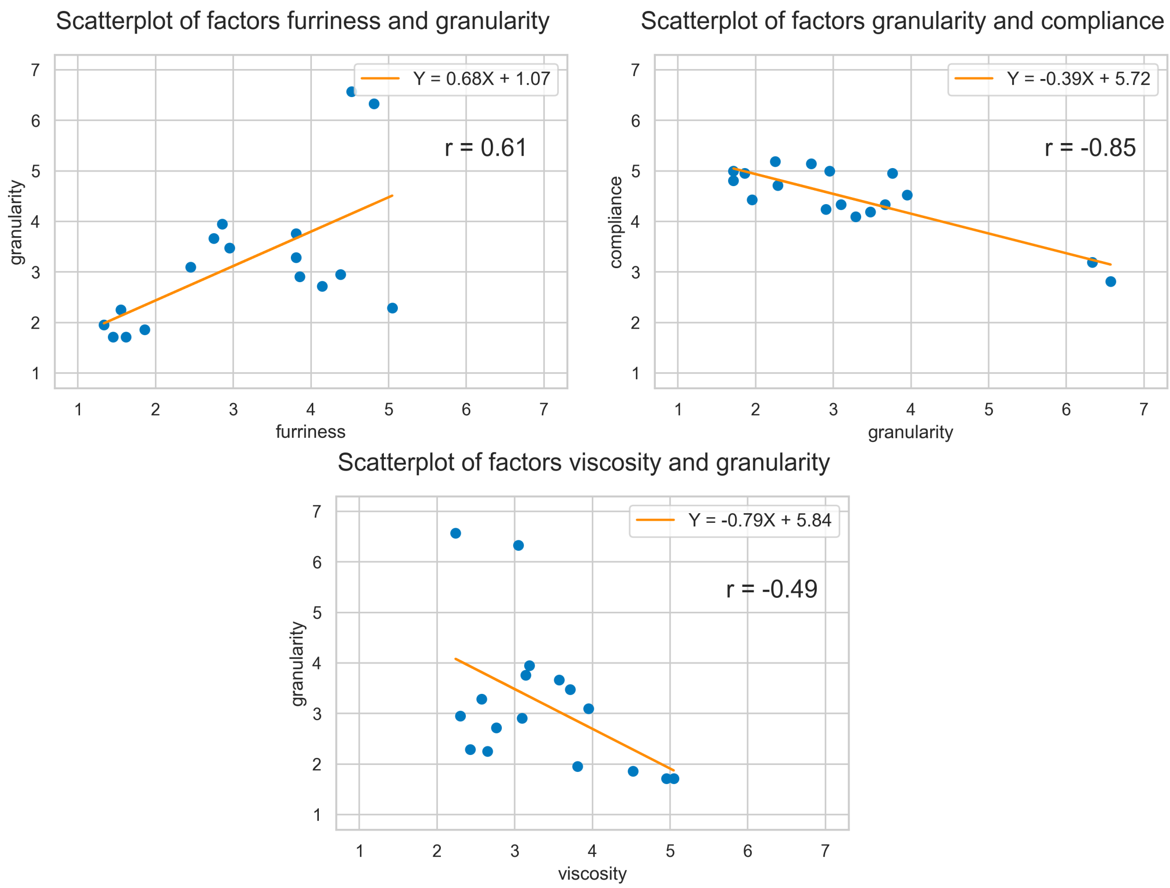

Figure 36: Scatterplots with regression line. The top left image factors are furriness on the x-axis and granularity on the y-axis. The top right has granularity on the x-axis and compliance on the y-axis. The bottom image has factors viscosity on the x-axis and granularity on the y-axis.

Figures 36 and 37 show the relationships between the four associated dimensions of softness. Starting with the factors furriness and granularity, a moderately positive relationship was observed, $r=.61$, $p<.01$. The factors compliance and granularity showed a strong negative relationship $r=-.85$, $p<.01$. Furthermore, the factors granularity and viscosity had a moderately negative relationship, $r=-.49$, but $p>.01$.

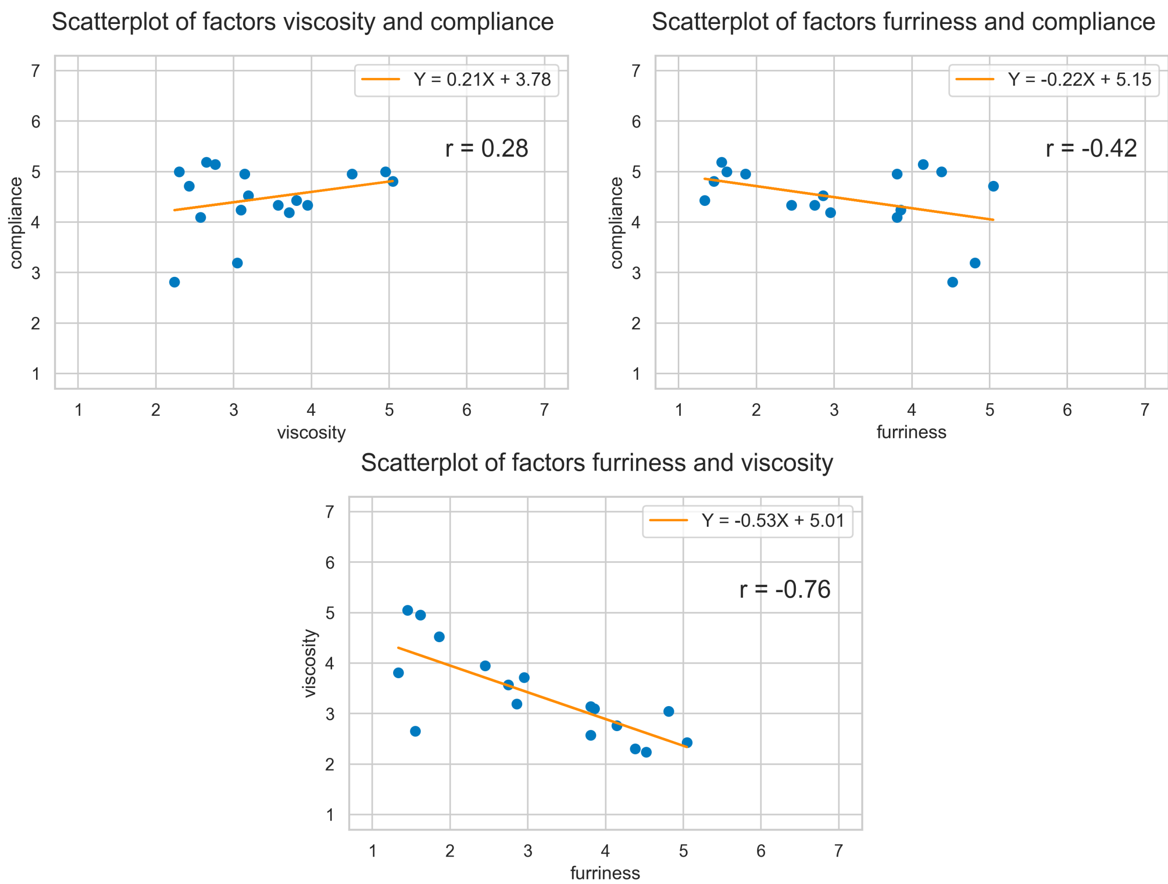

Figure 37: Scatterplots with regression line. The top left image factors are viscosity on the x-axis and compliance on the y-axis. The top right has furriness on the x-axis and compliance on the y-axis. The bottom image has the factors furriness on the x-axis and viscosity on the y-axis.

The top left linear regression image of figure 37 shows a weak relationship between the factors compliance and viscosity, $r=.28$, $p>.01$, this also applies to the factors compliance and furriness, $r=-.42$, $p>.01$. Finally, factors viscosity and furriness were correlated negatively, $r=-.76$, $p<.01$.

6.3 Discussion

In this section, the following research questions will be answered and a selection of materials to use in Study 3 will be made:

- **SQ1 How are the qualities of soft materials (varying in compliance, granularity viscosity and furriness) perceived when passively applied to the forearm?**
  - **SQ1.1 How do passively applied materials (varying in compliance, granularity, viscosity and furriness) on the forearm relate to softness?**
  - **SQ1.2 How do passively applied materials (varying in compliance, granularity, viscosity and furriness) on the forearm relate to each other?**

SQ1.3 What are representative and available soft materials that resemble these textural qualities in passive touch?

The first goal of this study was to find a **selection of materials** to use in Study 3. For this study, the materials Fur fabric, 3D-printed PLA and Bubble wrap were selected. This decision was based on the softness ratings for these materials. Since the affective responses of materials validated as soft and hard were studied broadly. With Fur a material was selected that rated the highest on furriness and softness, with 3D-printed PLA a texture was selected that scored the highest on granularity and lowest on softness. At last, the texture Bubble Wrap was selected since its ratings for the four dimensions were widely distributed and thus interesting to further investigate in a future study.

This study gave valuable insights into how the associated four dimensions of softness were experienced in passive touch. More details about the results will be elaborated here.

Firstly, to answer **SQ1.3**, the results of the **Material Scatterplots** will be discussed in more detail. In this study, the texture qualities of various materials were investigated. Firstly, it was found that none of the materials that were tested scored only high on one factor and low on the others. This could suggest that the different texture qualities could be often interlinked and cannot be evaluated separately. When looking at the texture quality furriness, it was discovered that all the fabric materials that were chosen for the furriness factor scored high on softness and compliance. This indicates a correlation between these texture qualities. Besides, in the study by Yang and Zhu [50], five fabric materials, silk, flax, wool, cotton and leather were passively received around the wrist and rated based on the tactile properties softness, slipperiness, roughness and warmth. Out of these materials Leather and Modal fabric (similar to cotton) were also used in this study and when comparing their mean softness ratings, leather was experienced as almost two times as hard as was the same for modal or cotton to be experienced as almost two times as hard. A possible clarification for this could be that fewer textures were used and in a counterbalanced order instead of a random order. This could have resulted in different references based on how soft the textures felt. Moreover, 5-point Likert scale questions were used to rate the textures, whereas in this study a 7-point Likert scale was used. Furthermore, another difference was that their textures were applied around the wrist and in this study on the forearm. Another remark was that in this study it was found that the ratings for most textures were widely scattered and hence unwise to look only at the mean values as they did [50]. Additionally, some materials proved difficult to rate. For instance, Bubble Wrap, Rubber, and Aluminium Foil were challenging to categorize, making it hard to place them in one of the four categories. This showed that the evaluation of these materials' texture quality was difficult to interpret when passively received and also without orally and visually experiencing the material. The quality of viscosity was another challenging factor to interpret. In most scatterplots, the viscosity ratings were widely spread, which made it difficult to make conclusive evaluations. Nonetheless, it was found that materials with viscosity characteristics like slime, humid-cleaning wipes, and latex gloves had high viscosity ratings. This indicated that when a material lacked a specific viscosity characteristic, it was generally difficult to judge the viscosity when passively received on the forearm. However, when a material had a viscosity characteristic it was also perceived. In summary, the scatterplot results suggest that texture qualities were often interlinked and difficult to evaluate separately. Furthermore, some materials were difficult to interpret when passively received on the forearm, this should be considered in future research.

To answer **SQ1.1** and **SQ1.2** the results of the **Regression Plots** will be examined in more detail. By reflecting on the study, several key factors emerged from the regression plots regarding how humans experience the softness of materials through touch. It was found that the more granular a material, the harder it was perceived. Probably because the granularity textures were experienced as rough textures that were perceived as less soft. In addition, the dimension granularity was difficult to imitate, because of its characteristics. It was impossible to implement granular materials like loose sand or beads for example into the sleeve. Therefore the granularity factor represented roughness the best by looking at its negative relationship with softness and its material characteristics which was also observed in studies by Ekman et al. [13], Hollins and Risner [23]. Additionally Hughes et al. [25] claimed that in order to discriminate textures by touch, the roughness dimension was the most dominant attribute of textures. In this study, the materials that were selected to be rough or granular also scored unanimously high on roughness. In general, it was indeed found that roughness was the most constant property and the least distributed property for all materials. However, this was not the case for furry and fabric materials since these ratings for roughness were more widely distributed than for other materials. Interestingly, it was found that viscosity and furriness had little influence on how soft a material was experienced in passive touch. Contrarily to the active touch study conducted by Cavdan et al. [8], where instead of a single movement, participants used combinations of movements to optimally explore the materials [8]. In their study, it was found that the more furry a material, the softer it was experienced and the more viscose a material the harder it was experienced. In addition, in this study, it was discovered that the compliance of a material was closely related to its perceived softness which was similar to Cavdan et al. [9] and other studies about texture dimensions [3, 13, 23, 37]. In addition, this study suggested that compliant materials were perceived as less granular, which likely contributes to their perceived softness. Furthermore, furriness was found to be related to viscosity. The furrier a material was experienced, the less viscous it felt. Similarly, both granularity and furriness qualities were found to have a negative relationship with viscosity. This implied that materials that were highly granular or furry were perceived as less viscous. Finally, an above-average positive relationship between granularity and furriness was found. This indicated that the two factors may be related and that hairy materials also feel a little granular.

Consecutively, there were some **challenges** in material selection and implementation, as all materials had to be flexible to fit into the sleeve and at the same time perceive a stimulus. It was difficult to incorporate granular materials, like loose sand or beads, into the sleeve. This resulted in materials that represented roughness better than granularity. Similarly, it was impossible to include liquid-like viscous materials, such as honey or water, in the sleeve. However, Humid-Cleaning-Wipes represented cold and wet textures and slime a sticky texture. During the experiment, participants were asked to answer 85 questions about 17 different textures (when including no texture). Although it could be completed within 30 minutes it still required significant effort and caused some participants to lose focus. This possibly led to missing data and or deviant data towards the end of the survey. Finally, all participants had to disinfect their left arm, which probably caused some of the textures to feel stickier than intended. Overall these challenges influenced the results but not in a disturbing way.

Overall, despite the challenges, the study found some interesting insights and results about passively perceiving different textures. One of the most interesting findings was that the factors viscosity and furriness had little influence on how soft a material was perceived. This was contrary to the findings of Cavdan et al. [9] where active touch was used. Moreover, it was found that the factors roughness and compliance were negatively related to each other which implied that the more compliant a material the less rough it was perceived. With the results of this study, three materials were selected to use in Study 3 and thereby the material characteristics of 17 textures were validated for passive touch to be used in future research.

7

Study 2

This was the second study out of three in total. This chapter contains the study design, the results of the experiment and a discussion about the results. The study design was similar to that of Study 1 and only the differences will be addressed.

7.1 Study design

The goal of experiment 2 was to explore if there is an effect between a pressure stimulus applied on the forearm (varying in force and duration) and the affective response it evokes in humans. To capture participants' affective responses, qualitative methods EmojiGrid to capture valence and arousal and a Check-All-That-Applies (CATA) list with emotional words were used in combination with a quantitative method of a Smartwatch that captured arousal levels based on heart rate.

7.1.1 Participants

19 people participated in this study with an average age of: 27.05 years and sexes: 13 Females (68.42 %) and 6 Males (31.58%). A session had a total duration of approximately 20 minutes. The same exclusion regulations as in Study 1 were applied, thereby all participants differed from Study 1.

7.1.2 Stimuli

In each set-up, two variables with three levels for each variable were varied, to apply nine different stimuli two times, thus a total of 18 stimuli. The variable force had levels of: 0.3 bar (30 kPa), 0.4 bar (40 kPa) and 0.5 bar (50 kPa) and the variable duration had levels of: 0.5, 5.0 and 6.5 seconds. Whereof the variable duration was transcribed with the words 'pat' (duration of 0.5 sec), 'touch' (duration of 5.0 sec) and 'grab' (duration of 6.5 sec). All stimuli were applied in random order and combination. As described in the Setup-Design chapter these values for force and duration were based on literature and limitations of the McKibben Sleeve.

7.1.3 Procedure

Before the start of the experiment, the same forms as in Study 1 had to be completed, the same setup is used and a word definition list covering 25 emotional words was presented. Thereby like in Study 1 the participant's left arm was used and oral and visual influences were tried to be kept minimal. While completing the forms a smartwatch around the participant's right arm was used for a baseline measurement of the participant's heart rate for the first 100 seconds. After completion, participants' arousal and heart rates were captured with the application called Sense-It developed at the University of Twente. At the start of the experiment, the sleeve was adjusted to fit the participant's arm. After applying a stimulus the participant filled out a survey about the emotions the stimuli evoked. The survey consisted of an EmojiGrid to capture the valence and arousal levels and a Check-All-That-Applies list (CATA) of 25 words that covered multiple emotions, see Appendix A.2 for more details about the survey. After a stimulus, the participant had to fill out the EmojiGrid first, whereafter the same stimulus was applied again and the participant had to fill out the CATA list. Hereafter 'yes' or 'no' were answered to the question of whether both stimuli felt the same. After which the next stimulus was applied until all 9 pressures had occurred. Finally, at the end of the experiment, the participant was thanked for their participation and any questions about the study were answered.

7.1.4 Measures

Like in Study 1 ActivePresenter 8 was used as a survey tool and in this study to assess participant's affective responses to different pressure stimuli. The survey consisted of 37 questions in total for 9 different stimuli. After the first stimuli, the participant had to select a point in the EmojiGrid [43] image that reflected how pleasant (x-axis) and intense (y-axis) the stimuli felt, see Figure 38. Furthermore, a list of 25 emotional words was used to capture the emotional response of a stimulus in words. This list was defined based on previous studies by Guest et al. [18], Weda et al. [49] which resulted in the following CATA-list: Aggressive, Annoying, Arousing, Calming, Comfortable, Comforting, Delicate, Endearment, Exciting, Frightening, Gentle, Happy, Human, Indifferent, Irritating, Loving, Pleasurable, Sensual, Shocking, Supportive, Surprising, Thrilling, Unpleasant, Uplifting, Upset. During the experiment, participants could use a definition list explaining all words in the CATA list. Furthermore, it was thought that a list of 25 words was a good amount to show to the participant and also captured a broad range of emotional words. Lastly, after the stimulus was applied two times and both questions were completed, the participant had to answer if both stimuli felt the same. This was asked to indicate if there was something wrong with either the attachment of the sleeve or the sleeve itself. Overall, a survey was made where participants' affective responses were captured with words and numbers.

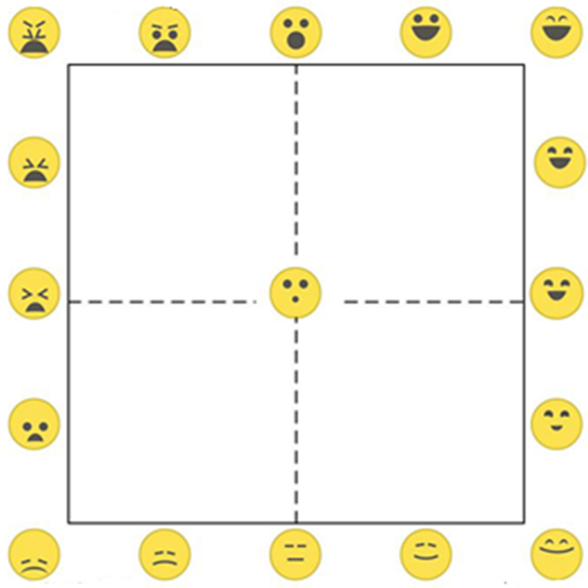

Figure 38: Emojigrid developed by Toet and van Erp [43], with arousal on the y-axis and valence on the x-axis.

7.1.5 Data Analysis

In this study, Python 3 was utilized for both data cleaning and analysis. Herefore, the modules Statistics, Scipy, Statsmodels, Scikit posthocs, and Matplotlib, were used to analyze and verify the assumptions for data analysis. The same data cleaning procedures as in Study 1 were applied, with one exception. Specifically, the EmojiGrid data was cleaned differently due to its unique nature. Firstly the Emojigrid responses were rotated to match the EmojiGrid axes, and subsequently, the EmojiGrid scores were converted from 0-100 per cent to a 9-point Likert scale for both axes. Furthermore, the data was matched with a randomized ordered list that paired each stimulus with its corresponding three questions. Before conducting the data analysis, the data was checked on various assumptions for conducting a two-way MANOVA. This included the number of dependent and independent variables, independence of observation, the absence of univariate or multivariate outliers (Mahalanobis distance), multivariate normality, linear relationship between independent and dependent variables, Levene's test of homogeneity of variance, and no multicollinearity. Every assumption was met except for multivariate normality, which meant that MANOVA could not be used, as this test presupposes multivariate normality, see Appendix A.3 for more details about the assumptions. Instead, the Kruskal-Wallis test was selected which is ideal for working with non-normally distributed data.

7.2 Results

Table 5: Descriptive Statistics of Valence, obtained from the EmojiGrid and ranging from 1 (least pleasant) to 9 (most pleasant), number of participants = 19.

N=19		Mean	Median	Variance	SD	Min	Max	Q1	Q3
Duration (seconds)	**Force (bar)**								
6.5	*0.3*	5.68	5.46	1.61	1.27	3.55	7.72	4.87	6.90
	0.4	5.33	5.68	1.80	1.34	2.93	7.37	4.80	6.12
	0.5	5.19	4.97	1.94	1.39	2.64	7.49	4.34	6.37
0.5	*0.3*	5.43	5.00	0.86	0.93	4.22	7.56	4.93	5.89
	0.4	5.01	4.95	1.43	1.20	2.67	7.97	4.44	5.47
	0.5	5.11	4.98	1.16	1.08	2.89	7.28	4.37	5.82
5.0	*0.3*	5.23	4.98	2.49	1.58	2.39	8.10	4.62	6.00
	0.4	5.41	4.97	2.39	1.55	2.43	8.11	4.67	6.65
	0.5	5.58	5.77	1.90	1.38	2.33	7.20	4.65	6.92

Table 6: Descriptive Statistics of Arousal obtained from the EmojiGrid and ranging from 1 (least aroused) to 9 (most aroused), number of participants = 19.

N=19		Mean	Median	Variance	SD	Min	Max	Q1	Q3
Duration (seconds)	**Force (bar)**								
6.5	*0.3*	3.09	2.76	2.16	1.47	1.10	6.14	2.08	4.43
	0.4	4.18	4.16	3.20	1.79	1.53	7.89	2.82	5.02
	0.5	4.84	4.96	1.83	1.35	2.69	7.50	3.75	5.76
0.5	*0.3*	2.99	2.60	2.04	1.43	1.23	5.99	1.87	4.26
	0.4	3.62	2.87	3.76	1.94	1.13	7.24	2.29	5.28
	0.5	3.97	4.22	3.66	1.91	1.31	7.68	2.43	4.96
5.0	*0.3*	3.55	3.24	2.07	1.44	1.38	6.67	2.69	4.06
	0.4	3.89	3.77	2.08	1.44	2.08	7.68	2.85	4.32
	0.5	4.80	4.87	1.58	1.26	2.80	7.62	3.96	5.51

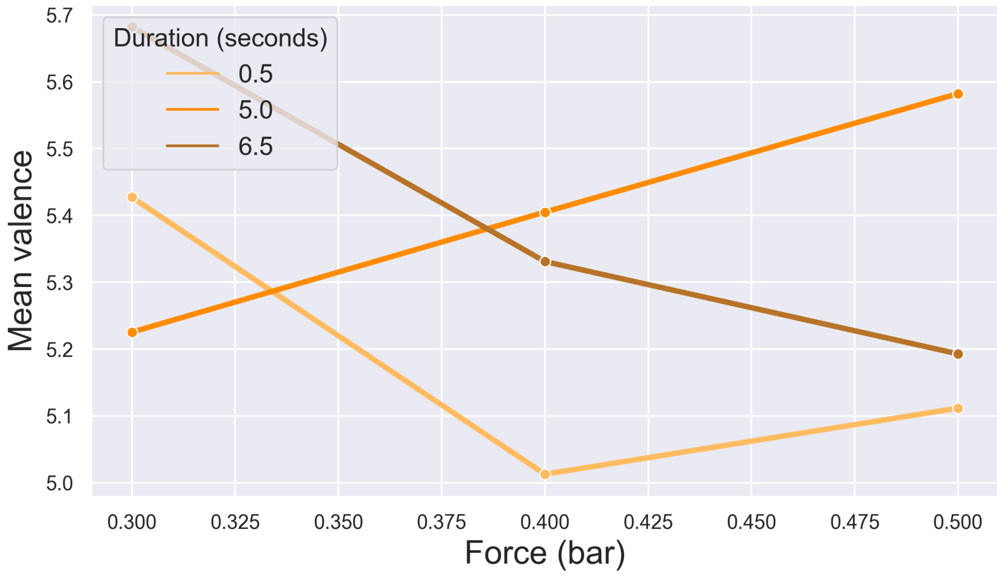

Figure 39: Line plot of mean valence responses for the three different durations. With on the x-axis pressure force (ranging from 0.3 to 0.5) and on the y-axis the mean valence response (ranging from 1 to 9)

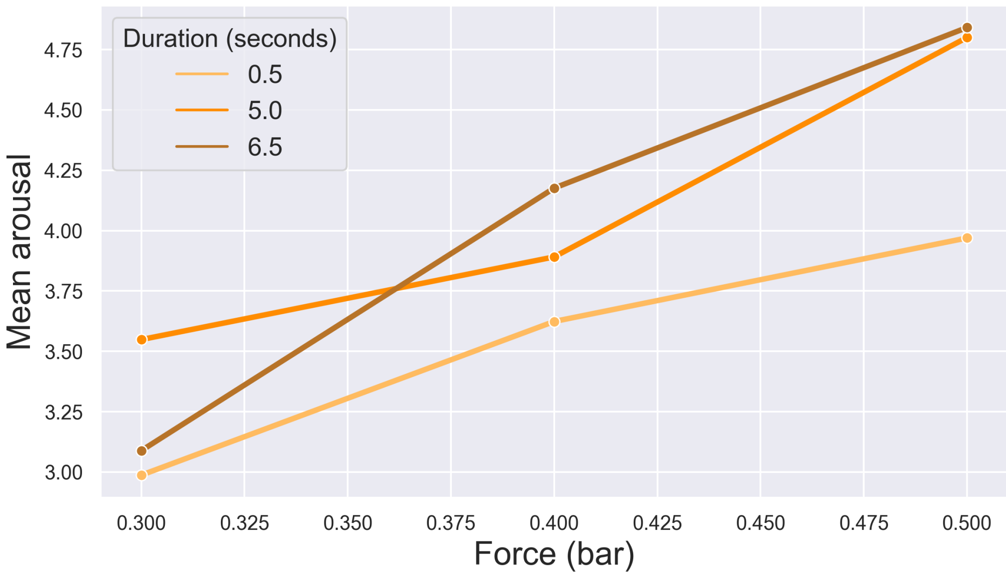

Figure 40: Line plot of mean arousal responses for the three different durations. With on the x-axis pressure force (ranging from 0.3 to 0.5) and on the y-axis the mean arousal response (ranging from 1 to 9)

Firstly the results of the EmojiGrid will be addressed. Figure 39 and Table 8 show that the mean responses for valence varied based on the amount of pressure force and duration. However, no clear observable relationship between force, duration and the valence response can be observed. Moreover, Figure 40 and Table 9 show that for all three durations, the mean response for arousal increases when more force is applied. To validate this finding a Kruskal-Wallis test was conducted to evaluate the emotional response of participants as reflected in the EmojiGrid. Pressure force and pressure duration were used as within-subject independent variables, and the scores for the dimensions of valence (x-axis) and arousal (y-axis) as two dependent variables. The results of the test revealed that there was a statistically significant difference in valence and arousal based on pressure force and duration, with $F = 64.49$ and $p<0.0000$. Further analysis revealed that force had a significant effect on the arousal axis score, with $F=18.7$ and $p=.000009$. A Dunn's post hoc test with a Bonferroni correction revealed that only two factors were statistically different, with a p-value of 0.00005. These factors were forces of 30kPa and 50kPa. For these factors, it was found that the pressure force had an effect on arousal, such that the emotional response was higher for high forces compared to low for lower forces. However, there were no significant effects of pressure force and duration on the valence axis score. Additionally, there were no significant effects of pressure duration on the arousal axis score.

Here the emotional words gathered by the CATA list will be addressed. In Figures 41, 42 and 43 word frequency bar plots are displayed. For each touch duration, a new bar plot image was created. For example, the grab touch gesture has a duration of 6.5 seconds where the bar colors represent the word frequencies per force stimuli, blue = 0.3 bar, orange = 0.4 bar and green = 0.5 bar. The frequency bar plot displays the frequency in percentage that a word is selected, note that it was possible to select multiple words.

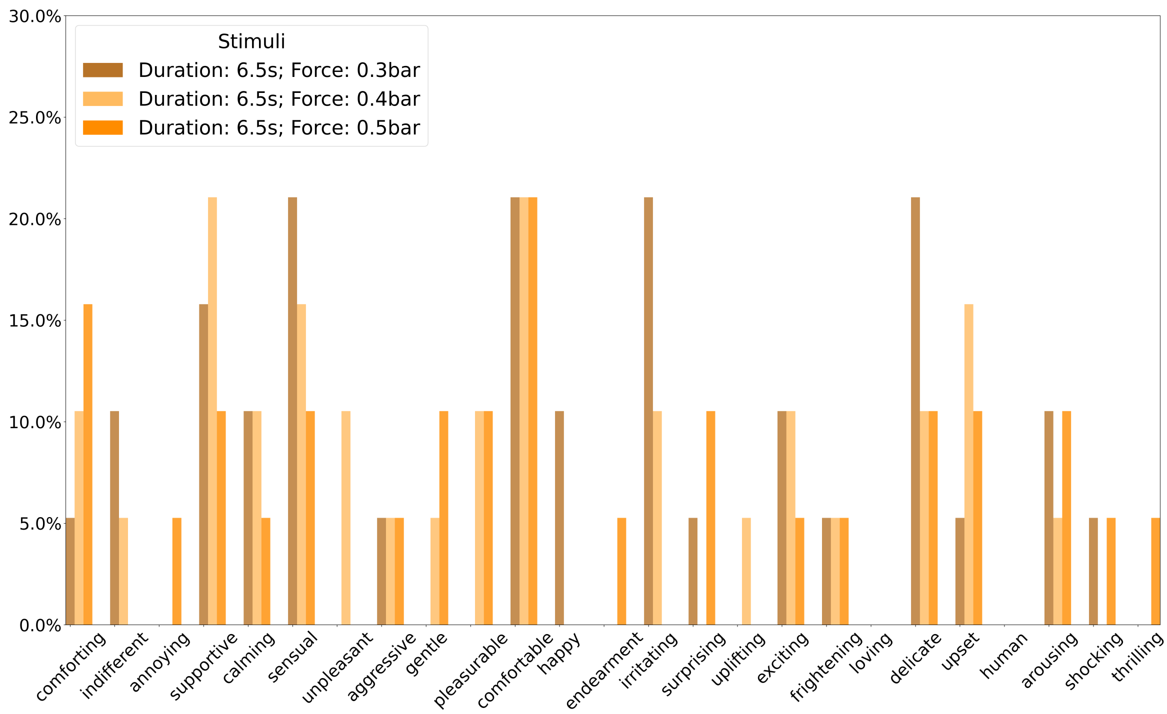

Figure 41: Emotional words bar plot of the grab gesture with a pressure duration of 6.5 seconds.

The distribution of responses for the grab gesture in Figure 41 was found to be widely spread. To better understand the participants' reactions, the words that were selected by 20% or more of the participants will be highlighted. When participants experienced a duration of

6.5s and a force of 0.3 bar, the emotions evoked were found to be "sensual", "comfortable", "irritating", and "delicate". For a duration of 6.5s and a force of 0.4 bar, the emotions evoked were "supportive" and "comfortable". Finally, when participants experienced a duration of 6.5s and a force of 0.5 bar, the most common emotion was "comfortable". Overall the grab gesture evoked mainly positive and relaxing emotions.

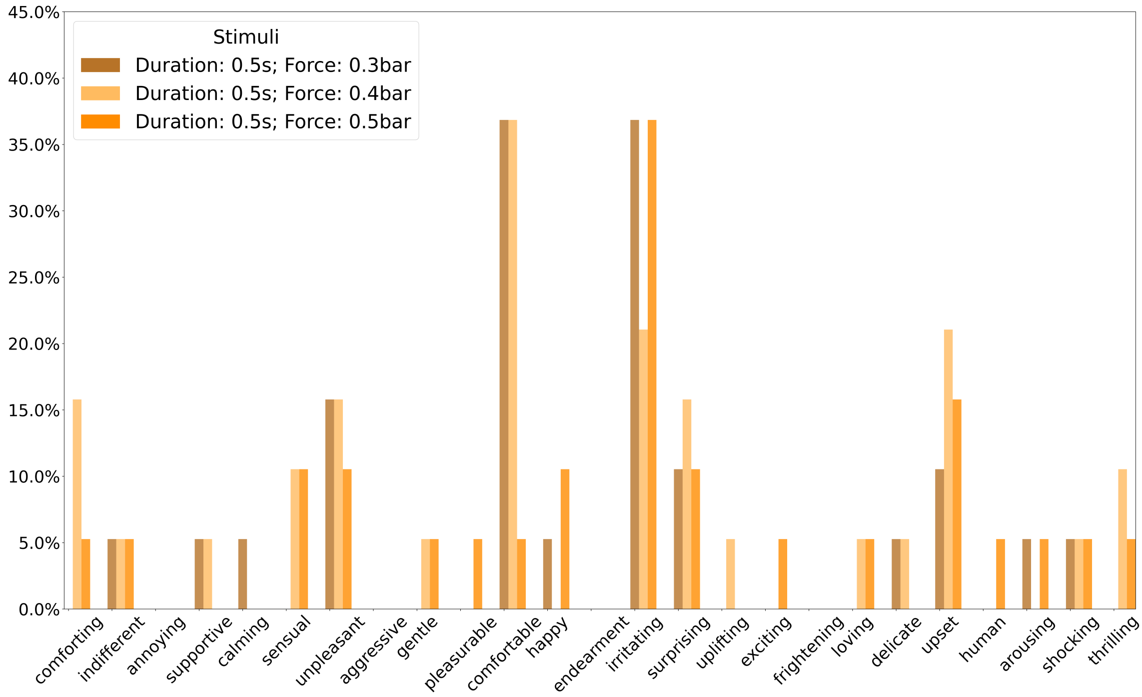

Figure 42: Emotional words bar plot of the pat gesture with a pressure duration of 0.5 seconds.

It was found that responses to the pat gesture with a duration of 0.5 seconds and forces ranging between 0.3 and 0.5 bar were more consistent than for the grab gesture, see Figure 42. Therefore, there will be looked at the words that were selected by 35% or more of the participants. When participants experienced a stimulus with a duration of 0.5 seconds and a force of 0.3 bar, the most commonly selected words to describe their experience were "pleasurable" and "irritating". For a stimulus with a duration of 0.5 seconds and a force of 0.4 bar, the most commonly selected emotion was "comfortable". On the other hand, a stimulus with a duration of 0.5 seconds and a force of 0.5 bar was found to be mainly "irritating". Overall a pressure duration of 0.5 seconds evoked either irritation or pleasant and relaxing emotions.

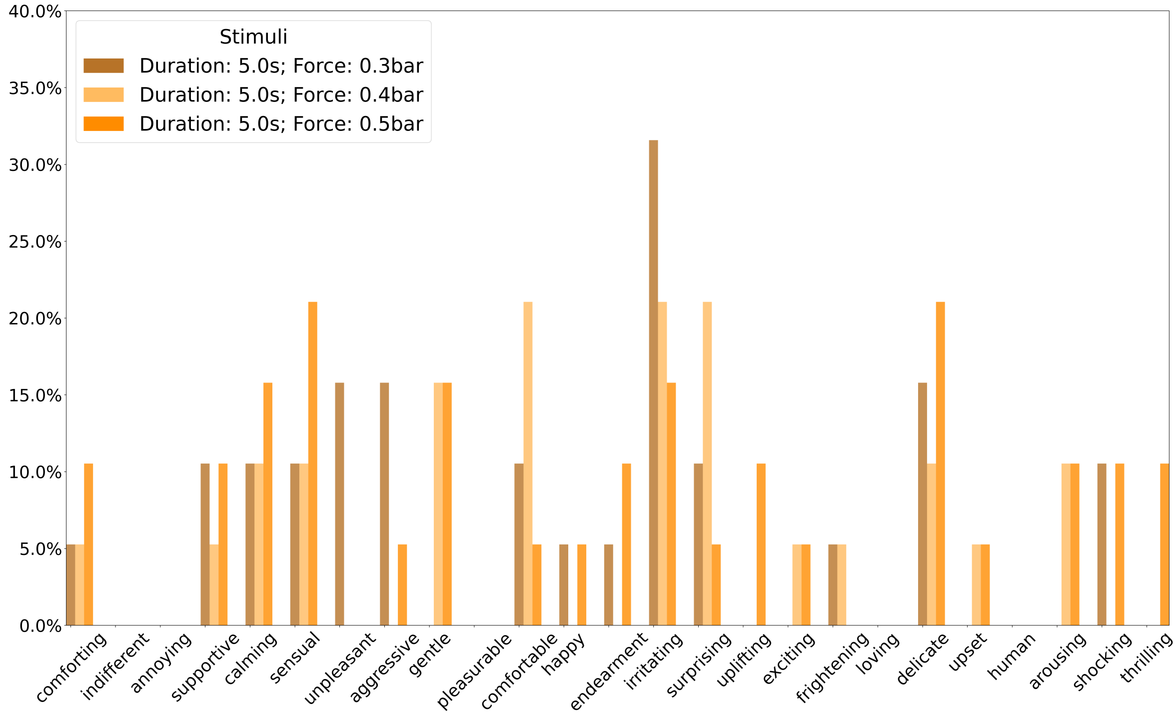

Figure 43: Emotional words bar plot of the touch gesture with a pressure duration of 5.0 seconds.

In this study, it was found that the responses to the touch gesture with a pressure duration of 5.0 seconds were once again more widely distributed. Therefore, only the words that were selected by 20% or more of the participants will be further discussed. When participants experienced a stimulus with a duration of 5 seconds and a pressure of 0.3 bar, the most commonly selected emotion was "irritating", reported by more than 30% of the participants. This stimulus was rated the most consistent for this gesture. For a stimulus with a duration of 5.0 seconds and a pressure of 0.4 bar, the most commonly selected emotions were "comfortable", "irritating", and "surprising". These emotions were selected by more than 20% of the participants. Finally, a stimulus with a duration of 5.0 seconds and a pressure of 0.5 bar was found to evoke mainly "sensual" and "delicate" emotional experiences, selected by more than 20%. Overall, out of the three gestures, the emotions evoked by the touch gesture vary the most. However the higher the pressure force the more pleasant the stimulus felt.

7.3 Discussion

This study was performed to find an answer to the following question:

Q1 What is the effect of passively received pressure stimuli gestures varying in force and duration on the forearm in evoking affective responses?

To answer this question the emotional responses elicited by different haptic stimuli using the **EmojiGrid** will be examined first. The results showed that the force of the stimulus had a significant effect on arousal response, with higher forces evoking higher levels of arousal. This finding was expected since the higher the force the more intense the stimuli would feel. Though this is in contrast to Weda et al. [49] where higher force resulted in lower arousal and lower force in higher arousal. A remark hereby is that in their study higher forces were used, namely of 5.6 kPa (0.6 bar) and 8.9 kPa (0.9 bar). Moreover, in this study, a significant effect of duration on the arousal or valence scores was not found. Interestingly, for both pressure variables force and duration, there were no significant effects for valence, indicating that the haptic stimuli did not evoke different valence. Overall, this suggests that the emotional responses elicited by the haptic stimuli were primarily related to arousal levels rather than valence where the force change was the most important factor.

Furthermore, this study also explored the **emotional responses** evoked by various pressure durations and forces in words. It was found that most of the stimuli evoked either comfortable or irritating sensations or both. One of the gestures that was investigated was the grab gesture, which elicited a wide range of emotional responses from participants. It was expected that this stimulus with a duration of 6.5 seconds be the most calming or awkward one since it had the longest duration. However, it was found that for all pressure forces, the word comfortable was selected by more than 20% of the participants, while words like frightening or unpleasant by only 5% of the participants, indicating that this duration was mostly calming instead of awkward. The responses to the pat gestures were also examined and were the most consistent among the tested gestures. Specific combinations of duration and force were associated with particular emotional responses, such as "pleasurable", "irritating", and "comfortable". Interestingly, for all pressure forces, the emotional word irritating was selected the most, above 20%. This was expected from the pat gesture, as it had a very short duration of only 0.5 seconds, similar to poking someone and to findings of Zhu et al. [54] where fast patting evoked anger and annoyance emotions. However, a contrary expectation was that this stimulus was also experienced as comfortable, especially for low and medium forces, with responses above 30%. The pat gesture was comparable to the study by Weda et al. [49] where a duration of 460ms was used with the McKibben sleeve, other durations were not investigated. Moreover, the emotional words of above 35% that this stimuli evoked were comfortable and gentle in this study these were comfortable and irritating. A possible explanation therefore was that contrarily to Weda et al. [49] there was no force transition used in this study. In other words, the stimulus was applied without any build-up of the pressure force, this could have resulted in irritatable emotional responses. Additionally, looking at the results of the touch gesture with a pressure duration of 5.0 seconds, it was found that the responses to this gesture were widely distributed. Whereby some combinations of pressure and duration were associated with specific emotional responses, such as "irritating", "comfortable", "surprising", "sensual", and "delicate". Touch was expected to be the most comfortable, as the duration lay between pat and grab. However, it was found that the word irritating was selected the most, at least above 15% of the responses, and even above 30% in case of a 0.3 bar pressure force.

There were some remarks while doing this study with the McKibben Sleeve. Firstly, the sleeve did not effectively produce human touch experiences, as indicated by the fact that the word "human" was only selected once. This aligns with the findings of previous research by [49], which reported that the McKibben sleeve was experienced as mechanical. Furthermore, by looking at the effectiveness of pressure durations used to imitate human gestures, it was found that the selected artificial gestures did not always evoke the desired emotions. Moreover, the durations were based on the gestures of the study by [51], however in that study the gestures were used to communicate certain emotions, but they did not investigate if this also elicit the same emotions in the touch receiver. Moreover, when comparing the touch gestures grab, touch and pat with the study by [51], the only relatable word was that of relaxed.

As it related to the words comfortable and delicate, which were frequently selected words in this study. Additionally, some participants experienced difficulty with the sleeve's fit, as their arm sizes were either too thick or too thin. This caused issues with closing or tightening the sleeve, which may have affected their perception of the stimuli. Furthermore, the yes/no question, which was used to gauge whether participants noticed any differences between two consecutive stimuli, was often misinterpreted. Rather than comparing the same stimuli one applied before the EmojiGrid and applied before the CATA list, participants thought the question was about whether the last two stimuli felt different from the previous two stimuli. As a result, the data collected from this question was deemed unusable. Finally, participants reported difficulties in perceiving the stimuli, particularly at the start of the experiment when they did not know what to expect. Specifically, the pressure duration of 0.5 seconds and 0.3 bar was the most difficult to perceive. These findings suggest that there exist limitations to the effectiveness of the McKibben sleeve in producing human touch experiences, and further research is necessary to improve its functionality.

8

Study 3

This was the third and last study. This chapter contains the study design, the results of the experiment and a discussion about the results. The study design was similar to that of Study 1 or Study 2 and only the differences will be addressed.

8.1 Study design

Our goal of this experiment was to explore if there is an effect between the affective responses that different textures evoke. Three textures validated in experiment 1 were passively applied to the forearm. These textures were selected based on softness, where Fur fabric was experienced as the softest, 3D-printed PLA as the hardest and Bubble foil as the most scattered. Like in Study 2 the EmojiGrid and CATA-list were used as qualitative methods to capture the responses in combination with a Smartwatch that captures the arousal levels based on heart rate.

8.1.1 Participants

A total of 24 people participated in this study with an average age of: 25.13 years and sexes: 11 Females (45.83 %) and 13 Males (54,17%). The study had a total duration of approximately 10 minutes. The same exclusion regulations as in Study 1 were applied, thereby it was not allowed to participate in this study if a participant also participated in Study 2, this was not the case if they already participated in Study 1.

8.1.2 Stimuli

In each set-up, a total of three different textures were varied: Bubble foil, 3D-printed PLA and Fur fabric, see Figure 44. The textures were applied one time in random order, thus a total of 3 stimuli. The force and duration of the pressure were kept constant, with a duration of 5.00 seconds and a force of around 0.4 bar (40 kPa). See Table 7 for the characteristics of the three textures.

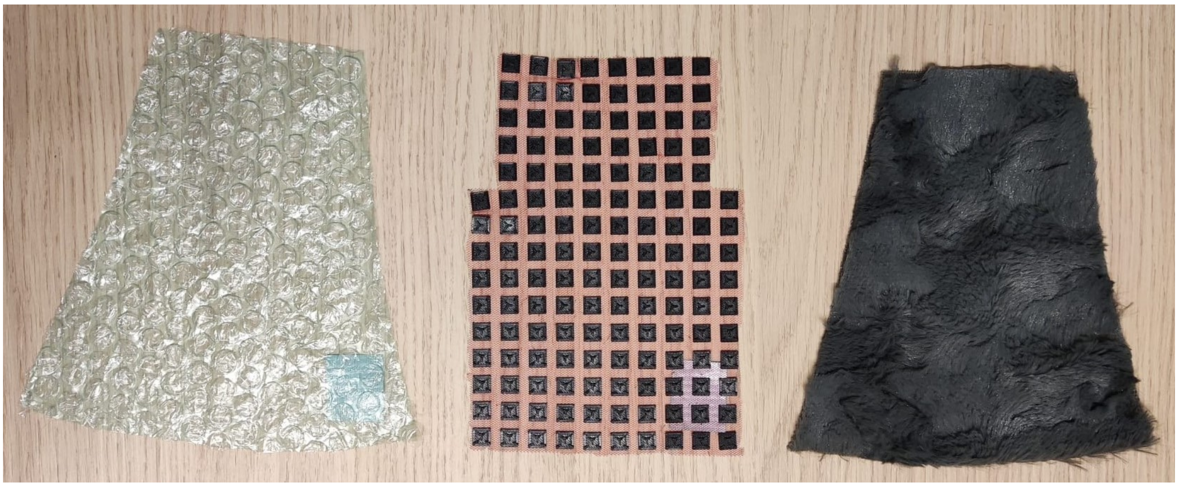

Figure 44: Fltr: Bubble Wrap, 3D-printed PLA and Fur fabric.

Table 7: Characteristics of the three textures. SCT stands for scattered, AA for above average and BA for below average. The $\bar{x}$ symbol represents the mean value for its material property.

Texture	Compliance	Granularity	Viscosity	Furriness	Softness
Bubble Wrap	AA ($\bar{x}$=4.33)	SCT ($\bar{x}$=3.10)	SCT ($\bar{x}$=3.95)	SCT ($\bar{x}$=2.45)	SCT ($\bar{x}$=4.00)
PLA	BA ($\bar{x}$=2.81)	High ($\bar{x}$=6.57)	Low ($\bar{x}$=2.24)	SCT ($\bar{x}$=4.52)	Low ($\bar{x}$=1.62)
Fur fabric	SCT ($\bar{x}$=4.71)	Low ($\bar{x}$=2.29)	Low ($\bar{x}$=2.43)	High ($\bar{x}$=5.05)	High ($\bar{x}$=5.86)

8.1.3 Procedure

Before the start of the experiment, the same forms as in Study 1 had to be completed, the same setup was used and a word definition list covering 25 emotional words was presented. Thereby like in Study 1 the participant's left arm was used and oral and visual influences were tried to be kept minimal. Like in Study 2, a smartwatch with the Sense-It application was used for a baseline measurement to capture the participant's heart rate. At the start of the experiment, the sleeve was adjusted to fit the participant's arm. After applying a stimulus the participant filled out a survey about the emotions the stimuli evoked. Like in study 2, the survey consisted of an EmojiGrid and the same CATA list. After a stimulus, the participant had to fill out the EmojiGrid first and thereafter the CATA list. Hereafter the sleeve was opened by the executor to replace the texture up to two times. Finally, at the end of the experiment, the participant was thanked for their participation and any questions about the study were answered.

8.1.4 Measures

The same survey as in Study 2 was used with two questions per stimuli which were EmojiGrid [43] and CATA-list. In addition, the survey consisted of 6 questions in total for 3 different stimuli. Furthermore, a smartwatch was used to capture heart rate and arousal levels. These arousal levels ranged from -3 to 5 where -3 represented not at all aroused and 5 very aroused.

8.1.5 Data Analysis

In this study, the data analysis was performed using various Python 3 modules, including Statistics, Scipy, Statsmodels MANOVA, Pairwise Tukey, and Matplotlib. Furthermore, the same data cleaning and converting steps as in Study 2 were applied. The data were matched with a randomized ordered list, which involved applying stimuli and matching them with the corresponding two questions. Before conducting the data analysis, several checks on the data were performed to ensure that the assumptions for conducting a one-way MANOVA were met. Various assumptions were tested, including the number of dependent and independent variables, independence of observation, no univariate or multivariate outliers (Mahalanobis distance), multivariate normality, linear relationship between IV and DV, Levene's test of homogeneity of variance, and no multicollinearity. Every assumption was met, except for the multivariate normality assumption, which was slightly off by a very small value (0.047 < 0.05), see Appendix A.4 for more details about the assumptions. However, the deviation from normality was minimal and it was unlikely to affect the validity of the results hence it was decided to continue with the MANOVA analysis.

8.2 Results

Table 8: Descriptive statistics of valence captured by the EmojiGrid, ranging from 1 (least pleasant) to 9 (most pleasant).

	Descriptive Statistics of Valence (N = 24)							
	Mean	*Median*	*Variance*	*SD*	*Minimum*	*Maximum*	*Q1*	*Q3*
Bubble Wrap	5.67	5.78	1.48	1.22	3.21	8.42	4.96	6.42
PLA	3.56	3.54	1.55	1.24	1.31	6.48	2.55	4.53
Fur	6.90	7.22	1.17	1.08	4.95	8.76	5.92	7.67

Table 9: Descriptive statistics of arousal captured by the EmojiGrid, ranging from 1 (least aroused) to 9 (most aroused).

	Descriptive Statistics of Arousal (N = 24)							
	Mean	*Median*	*Variance*	*SD*	*Minimum*	*Maximum*	*Q1*	*Q3*
Bubble Wrap	3.87	3.60	2.15	1.46	1.44	7.40	2.83	4.98
PLA	5.00	5.20	3.41	1.85	1.84	8.43	3.38	6.18
Fur	3.69	3.39	2.81	1.68	1.14	7.22	2.41	4.70

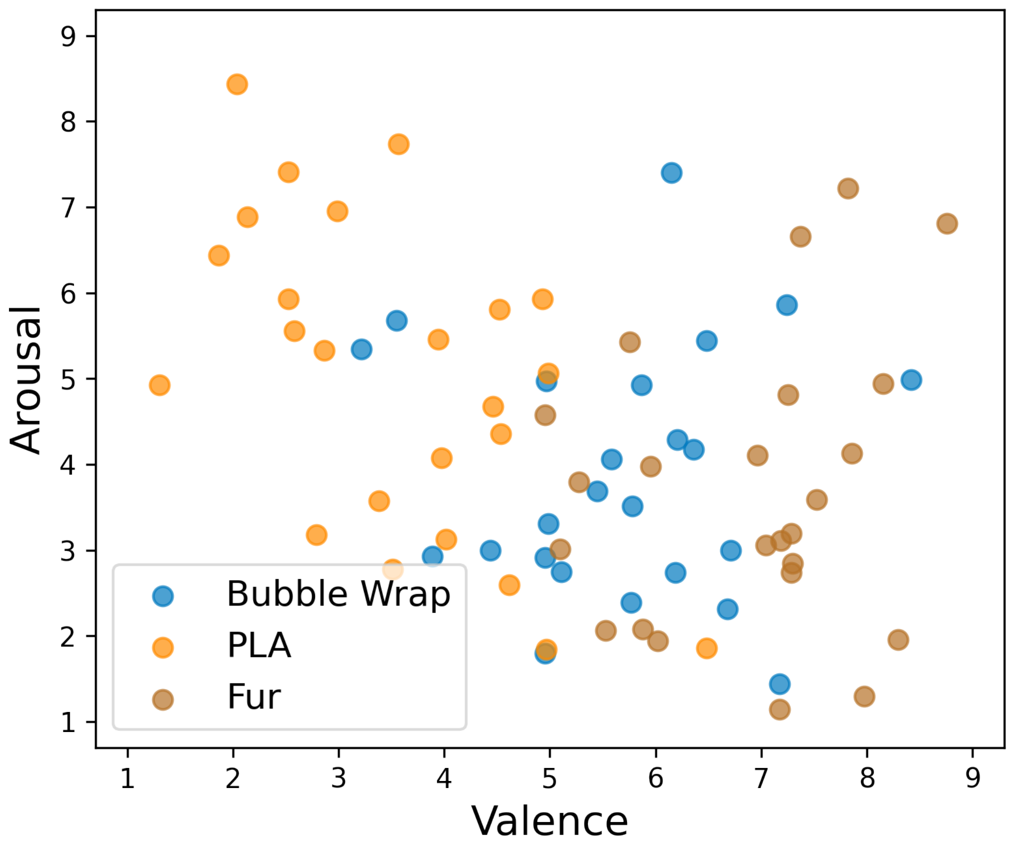

Figure 45: Scatterplot of the EmojiGrid responses for the three textures: Bubble Wrap, PLA and Fur

In this study, the data collected with the EmojiGrid to assess emotional responses were analyzed. The scatterplot, see Figure 45 and the descriptive statistics of valence and arousal, see Tables 8 and 9, show that PLA had the least pleasant and most aroused responses. Moreover, Bubble Wrap evoked average valence and arousal responses and Fur evoked the most pleasant and least aroused sensations. A one-way MANOVA was conducted with texture as the within-subject independent variable and valence and arousal as the two dependent variables. The alpha value was set at 0.05. The analysis revealed a statistically significant difference in valence and arousal based on texture F(4, 136)=19.40, p<.0000; Wilk's lambda = .41. Texture had a significant effect on arousal (F=4.32, p=.017) and valence (F=49.06, p=.0000). To explore the effects of texture on valence and arousal in more detail, a Tukey post hoc test was performed. The results of the Tukey test showed a significant positive effect (Meandiff=1.23, p=.0016) on valence when comparing the textures Bubble wrap and Fur. On the other hand, Bubble wrap compared with 3D-printed PLA had a significant negative effect (Meandiff=-2.11, p=.0000) on valence. Furthermore, the texture Fur compared with 3D-printed PLA also had a significant negative effect (Meandiff=-3.34, p=.0000) on valence. For the dependent variable arousal, there was no significant effect between the textures Bubble wrap and Fur. However, when comparing Fur and 3D-printed PLA, there was a significant positive effect (Meandiff=1.31, p=.022) on arousal. Notably, there was also a small positive effect on arousal for Bubble foil compared with 3D-printed PLA (Meandiff=1.12, p=.058). In summary, the analysis demonstrated that texture had a significant effect on both valence and arousal, with varying effects observed for different textures. These findings highlight the importance of texture in evoking emotional responses.

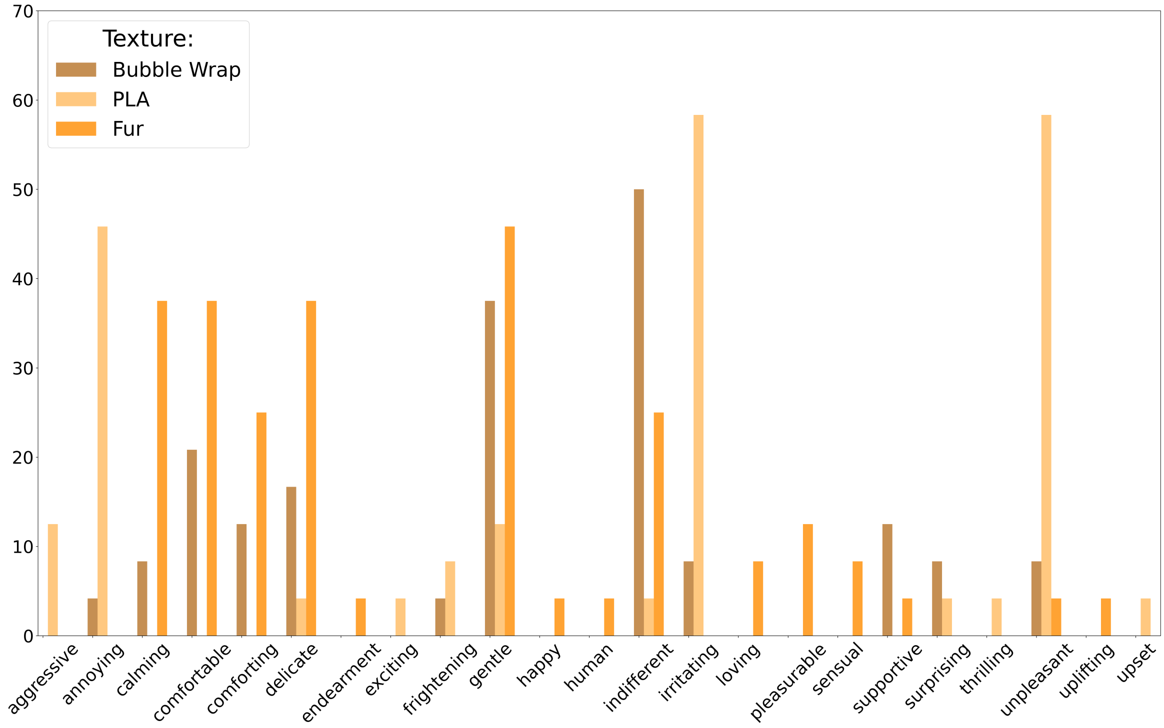

Figure 46: CATA bar plot of the three textures.

Additionally, data was collected with the CATA list and their corresponding word frequency bar plots were shown in Figure 46. The graph indicates that the data was specific and not too widely distributed, therefore the words that scored above 35% were highlighted. The analysis revealed that the Bubble wrap texture evoked the most frequent emotional words "indifferent" and "gentle". On the other hand, the PLA texture was associated with "annoying", "irritating", and "unpleasant" emotions. In contrast, the Fur texture was found to evoke "calming", "comfortable", "delicate", and "gentle" emotions. Notably, the word "gentle" scored high for both Fur and Bubble wrap textures. Overall, the emotional words evoked by each texture were very specific, with little overlap between textures.

All participants had to wear a smartwatch that captured their heart rate and arousal during the experiment. However, out of the 24 participants of only 14 participants usable data was acquired. The data had to be examined per participant and varied a lot. However the results of Table 10 indicate that the fur texture caused in 57% of the participants a fall in arousal and heart rate. Moreover, applying Bubble wrap and 3D-printed PLA largely did not change the arousal levels. Thereby the 3D-printed PLA texture rather caused an increase in stress than a decrease.

Table 10: Table representing the percentages that a texture caused a change or no change in arousal and heart rate.

N = 14	**Arousal level**		
Texture	*Down*	*No change*	*Up*
Bubble Wrap	21,43%	64,29%	14,29%
3D-printed PLA	7,14%	57,14%	35,71%
Fur	57,14%	21,43%	21,43%

All watch data graphs can be found in Appendix A.5

8.3 Discussion

This study is performed to find an answer to the following question:

Q1 What is the effect of passively received materials on the forearm, validated on compliance, viscosity, granularity, furriness and softness, on evoking emotions via a haptic device?

To answer this question, firstly there will be looked at the valence and arousal ratings of the **EmojiGrid**. Results revealed that different textures had a significant impact on their emotional response. Specifically, it was found that textures had a significant effect on the valence axis, where softer textures tend to receive higher valence ratings, and harder textures tend to receive lower ratings. Conversely, the hardness of a texture had a significant impact on the arousal axis, with harder textures evoking higher arousal ratings, and softer textures evoking lower ratings. Beforehand it was interesting to find out what the Bubble Wrap texture evoked in participants since this was the most difficult texture to rate in Study 1 due to its scattered responses. However, the results suggested that Bubble Wrap was experienced as a more neutral texture, with average ratings for both valence and arousal. Furthermore, the Fur texture rated the highest on compliance and furriness and was experienced as the most pleasant and least arousing texture. Contrarily the PLA texture was experienced as the hardest texture and rated the highest on roughness, evoking less pleasant and more aroused responses.

Additionally when looking at the results of the CATA list. The word frequency graph of **emotional words** revealed that Bubble Wrap evoked neutral and positive emotional sensations, PLA evoked negative emotional sensations, and Fur evoked positive emotional sensations. These findings were as expected and support the idea that the specific physical properties of a texture can influence the emotions it evokes. When considering the results of both Study 1 and Study 3 together, a texture that scored high on compliance and furriness was likely to evoke pleasant and calming sensations, whereas a texture that scored high on roughness and low on compliance was likely to evoke unpleasant and irritating emotional responses. The smartwatch data results supported the findings of Fur to evoke calming low aroused responses. Furthermore, the results suggested that a texture that was difficult to rate when passively applied was likely to evoke neutral emotional responses and gentle sensations. A general remark, some participants did not feel the contraction of the sleeve for the first stimulus. This was because the participants did not know what kind of stimulus to expect and the texture muted the sleeve contraction, especially the furry one. If this was the case, the sleeve was tightened and the stimulus was applied again. Overall the findings in this study were in line with previous studies showing that the texture of a material influences the emotions it elicits [14, 15, 18, 27, 50]. More specifically in past research soft materials were rated as more pleasant and harder materials as less pleasant.

In a previous study by Guest et al. [18] they found that perceived comfort increased with decreasing roughness, increasing slipperiness and increasing pile. To compare with this study, the term roughness is comparable with the term granularity, the term slipperiness with viscosity and pile with furriness. In other words the least rough and the more viscose and furry the texture the more comfortable it was perceived. In this study the affective response was captured via valence and arousal and not via comfortable, however, results of the bar plot for the furry material indicated high scores for comfortable, calming and comforting. Whereby the characteristics of the Fur texture were medium compliance, low roughness, low viscosity and high furriness. Like Guest et al. [18], this study also found the less rough and the more furry the more comfortable emotions it evoked. Contrarily, this study did not find a relationship with viscosity since the other study claimed that high viscosity leads to increased comfort, because non of the selected textures were found to be very viscose. Furthermore, they found that arousal increased with increasing roughness, firmness and pile. Again when translating these terms, the term firmness bests relates to not compliant. Thus, in other words, the more rough, furry and less compliant a texture the more aroused it was perceived. The 3D-printed PLA texture in this study evoked the most arousing responses and has the characteristics of medium compliance, high roughness, low viscosity and spread furriness ratings. Similarly, this study also found that high roughness evoked more aroused responses, but this did not relate to low compliance and high furriness as found in the other study [18]. Another study to compare with is that of Yang and Zhu [50], here five fabric materials are passively applied to the wrist. They found that their materials silk and fax that were perceived as softest scored higher on valence similar to this study. However, wool had the most negative ratings but was not perceived as the hardest out of the five, but was perceived as the most rough. Lastly, the affective ratings for cotton and leather were more balanced. Moreover, they propose that the rated valence of a stimulation tends to be correlated with the comfort of the textile material. Since for both the stroking and the squeezing stimulation, their results suggest that comfortable materials like silk causes more pleasant sensations than uncomfortable ones like wool. Hence it would be interesting to further research the affective response of dynamic stimulation of multiple textures.

In this study, there were a few limitations that should be considered. Firstly, only three textures were used, which limits the generalizability of the results to other textures. Secondly, for the materials used in this study, viscosity was either low or scattered. Therefore, the influence of viscosity on the emotional response could not be investigated. Additionally, the smartwatch data was difficult to interpret since it varied greatly per participant and of only 14 participants usable data could be obtained. This in combination with the short duration of the study may have caused the watch data to be less usable. Furthermore, it should be noted that the softest texture scored both high on the properties of furriness and compliance. On the other hand, the hardest texture had high roughness and low compliance. Therefore it was possible that compliance had the most significant influence on the emotional responses rather than furriness or roughness. Considering these limitations, future studies should investigate a broader range of textures, including those with high viscosity, to provide a more elaborated understanding of the influence of texture properties on emotional responses.

9

General Discussion

In this chapter, the main findings of the three studies will be discussed and compared to past literature. Starting with Study 1 followed by Study 2 and lastly Study 3. Whereby studies 2 and 3 will give answers to the two main research questions. Moreover, it will be discussed how these results contribute to future social-mediated touch devices. Lastly, the limitations of this research will be addressed.

9.1 Texture validation for passive touch

In Study 1, a total of 17 different textures were passively applied to the participant's left forearm using a haptic device called the McKibben sleeve. Participants rated these textures on the material properties of compliance, granularity, viscosity, furriness, and softness. With this study, 17 textures were validated for passive touch based on their material properties. By means of this validation, a selection of three textures was chosen for Study 3, to subsequentially capture the affective response these textures evoke in a haptic device. For this study, the materials Fur fabric, 3D-printed PLA and Bubble wrap were selected based on softness and the distribution of the other properties. With Fur a material was selected that rated the highest on furriness and softness, with 3D-printed PLA a texture was selected that scored the highest on granularity and lowest on softness. At last, the texture Bubble Wrap was selected since its ratings for the four dimensions were widely distributed and thus interesting to further investigate in a future study. A remark has to be made on the ratings on the granularity quality. Since, due to the limitations of passively applying these stimuli in a haptic device, the quality of roughness was best reflected by the granularity quality. Overall, the textures were found to be difficult to rate, as the responses were widely distributed. It was found that none of the materials that were tested scored only high on one factor and low on the others. This could suggest that the different texture qualities could be often interlinked and cannot be evaluated separately. Another study that passively explored different textures on material properties is that of Yang and Zhu [50]. Here five fabric materials were passively received around the wrist and rated based on the tactile properties of softness, slipperiness, roughness and warmth. A comparison can be made between both studies for the materials Leather and Modal fabric (similar to cotton). Hereof only the mean ratings of these materials were reported and when comparing material softness, they reported that leather was experienced as almost two times as hard as leather was in this study, the modal or cotton material had similar results. A possible explanation for this may have been due to the textures being applied around the wrist, in contrast to the forearm, and in a counterbalanced order, in contrast to a random order.

9.1.1 Relationship between material properties and softness

Looking at the results, claims can be made about the relationships between the material properties in passive touch. In the active touch experiment by Cavdan et al. [8], the qualities compliance, granularity, viscosity and furriness were found to be correlated with the softness of the material. In this study where passive touch is used, it was discovered that the compliance of a material was closely related to its perceived softness which was similar to Cavdan et al. [9] and other studies about texture dimensions [3, 13, 23, 37]. Moreover, a negative linear relationship was observed between softness and roughness. Lastly, no relationships were observed between softness and viscosity; and softness and furriness which is in contrast to the study by Cavdan et al. [8], where instead of a single static movement, participants used combinations of movements to optimally explore the materials and thus feel more characteristics. Additionally Bergmann Tiest [3] stated that roughness and coldness can be perceived statically thus with passive touch, whereas compliance and slipperiness have to be perceived dynamically through active touch. However, the results of the passive touch experiment suggest that compliance can also be perceived through passive touch, because a strong relationship was found between the softness and compliance of a material. A possible clarification, therefore, is that the haptic device used pressure that compressed the arm and the material causing the participant to feel the deformation of the material. Moreover, the furriness of a material can also be perceived passively, but not as strong as roughness and compliance. In general, it was found that roughness was the most constant property and the least distributed property for all materials and thus the most dominant attribute to discriminate textures by touch as [25] also claimed. Overall, the results of this study indicate that in passive touch the softness of a material relates to the compliance and roughness of a material. Therefore when implementing textures in future designs of mediated touch devices for passive touch, the roughness and compliance of a material are the most important factors to take into account. Since the more compliant the material, the softer it is perceived and the less rough and vice versa.

9.2 Affective responses of different pressure forces and durations

In this study, the McKibben sleeve was used to capture participants' affective responses evoked by various pressure forces and durations. Key findings of this study were that different pressure durations of 0.5 seconds, 5.0 seconds, and 6.5 seconds had no effect on valence and arousal. Furthermore, it was also found that different pressure forces of 0.3 bar, 0.4 bar, and 0.5 bar had a significant effect on arousal but had no effect on valence.

9.2.1 Answering research question

With this study, the second main question can be answered:

Q2 What is the effect of passively received pressure stimuli gestures, varying in force and duration, on the forearm in evoking affective responses?

Firstly, it was noted that arousal increased as the pressure force increased similar to Yang and Zhu [50], but in contrast to a previous study with the McKibben Sleeve by Weda et al. [49]

that reported that increasing force decreased arousal responses. A possible clarification for this difference is that in the study by Weda et al. [49] higher forces were used, namely that of 0.6 bar and 0.9 bar. Thereby their pressure area was smaller, 1 or 3 McKibbens in contrast to actuating 8 McKibbens at the same time. However, it could indicate that there exists a turnover point in arousal for higher pressures, but to investigate this, the same pressure areas have to be used to draw definite conclusions. Moreover, the duration of the touch had no effect on arousal and valence responses. This finding was in contrast to other studies that reported the opposite [50]. However, it was suggested that this could be because participants only felt the compression strike and the decompression strike, and the compression hold was not recognized clearly. Lastly, in terms of the emotional words selected by participants, the pat gesture with a duration of 0.5 seconds caused the most consistent answers. For this duration, light touch was experienced as either pleasurable or irritating, medium touch as pleasurable, and hard touch as irritating. When comparing this to the study of Weda et al. [49], the emotional words of above 35% that this stimuli evoked were comfortable and gentle, in this study these were comfortable and irritating. A possible explanation is that there was no force transition used in this study that may have caused irritating sensations and the contact area was larger in this study. CATA responses for the other touch gestures, grab with a duration of 6.5 seconds and touch with a duration of 5.0 seconds, were more distributed, making it difficult to draw conclusions. It was expected that the grab gesture with a duration of 6.5 seconds to be the most calming or awkward one since it had the longest duration. However, it was found that for this gesture the word comfortable was selected most, more than 20%. Furthermore, the touch gesture with a duration of 5.0 seconds was expected to be the most comfortable, as the duration lay between that of the gestures pat and grab. However, it was noted that the light touch gesture evoked mainly irritating sensations. A possible explanation is that the contact area may have distributed the pressure on the forearm causing the participants to feel mainly the contraction and retraction of the sleeve. Moreover, a bigger time between contraction and retraction could have led to irritating sensations. In general, all touch gestures mainly evoked calming sensations, this was as expected as [55] also reported that squeezing evokes relaxing and calming emotions. Overall, the main findings of this research were that pressure duration in passive touch had no effect on valence and arousal, where higher pressure evoked higher arousal responses.

9.3 Affective responses of textures

For the third study, three textures were selected based on their material properties and softness ratings. These textures were Fur fabric as it was perceived as the softest texture, 3D printed PLA as the hardest, and the Bubble wrap ratings were widely distributed but, in general, medium soft. The analysis of the results showed that texture had a significant effect on both valence and arousal, with varying effects observed for different textures.

9.3.1 Answering research question

The findings of this study answers the first main research question:

Q1 What is the effect of passively received materials on the forearm, validated on compliance, viscosity, granularity, furriness and softness, on evoking emotions via a haptic device?

Firstly, it was observed that the Fur texture evoked the most pleasant sensations with low arousal scores ($\bar{x}$ = 3.69). Moreover, this material scored high on valence ($\bar{x}$ = 6.90), and emotional words like calming, comfortable, gentle, and delicate were selected most often. Indicating that furry and soft materials will be perceived as pleasant. This was consistent with previous research [18], where furry materials were also found to evoke comforting emotions. Furthermore, the 3D-printed PLA material was validated as hard and rough and evoked unpleasant sensations with medium arousal scores ($\bar{x}$ = 5.00). As the valence response was low ($\bar{x}$ = 3.56) and the emotional words irritating and unpleasant were selected often. This finding was consistent with previous research [18], where rough materials were found to evoke less pleasant and higher arousal responses. The Bubble Wrap material was perceived as neutral on the valence axis ($\bar{x}$ = 5.67) with low arousal scores ($\bar{x}$ = 3.87). Moreover this material was selected because it was the most difficult to rate based on the five qualities of softness in Study 1. Because this material was difficult to determine, it may have resulted in neutral emotions as this material evoked emotional responses such as indifferent and gentle. Unfortunately, these results could not be compared to other studies, since there were no studies found that reported about Bubble Wrap like materials. Accordingly, it was observed that softer textures tended to receive higher valence ratings, while harder textures received lower ratings. On the other hand, the hardness of a texture had a significant impact on the arousal axis, with harder textures evoking higher arousal ratings, and softer textures evoking lower ratings. Overall, this was consistent with previous studies of passive touch on the forearm [14, 15, 18, 27, 50]. Since in those studies, different textures elicited different emotions and more specifically, soft materials elicited pleasurable sensations, while hard materials elicited unpleasant sensations. Results of the heart rate and arousal responses measured by the smartwatch indicate that the Fur material caused a reduction in heart rate and arousal in 57,14% of the cases. However, the data was very specific per person and only the moment in time was captured when the stimuli were applied. Hence other factors that could have influenced arousal fluctuation were not captured, such as when the participant's arm was placed or released from the sleeve. Moreover, the baseline measurement was only measured over the first 100 seconds. For example, people who were cycling fast just before they arrived at the experiment may have influenced the baseline measurement, because their heart rate usually dropped and a baseline measurement of 100 seconds was not sufficient for this. Therefore based on the smartwatch data, conclusions could not be drawn for the PLA and Bubble Wrap materials as mainly 'no change' in arousal was observed. However, in a study where participants are exposed to a stimulus for a longer period of time, it can be useful to use a smartwatch to capture arousal data responses.

Overall, based on the findings in this research of passively applying textures to participants' forearms, materials that scored high on the qualities of furriness and softness scored high on valence, low on arousal and evoked calming and relaxing emotions. In addition, rough and hard materials evoked low valence and medium arousal ratings and elicited irritating and unpleasant emotions. Lastly, textures that were difficult to identify by participants and had medium softness ratings evoked medium valence, low arousal ratings and mainly neutral emotions as indifferent.

With this research, answers have been obtained about how different textures are experienced in haptic devices that are controlled by pressure. These findings can be used in future haptic social-mediated touch devices. Moreover, the type of texture influences the affective response it evokes. Future research had to take this into account when designing haptic devices for mediated social touch. Since higher pressure for example increases perceived pleasantness for one material and could decrease it for another material. Furthermore adding audio and visual influences can enhance the experience even further as it is known that both senses influence the affective response. It would be interesting to investigate how for example a soft and furry material in combination with unpleasant visual and audio is perceived. Or how the experience of a neutral material like Bubble Wrap can be influenced by visual and audio cues. Overall, the type of texture enhances the emotional experience of haptic devices but has yet to be tested in a mediated social touch environment

9.4 Limitations

In the conducted studies, several limitations were identified that should be taken into consideration. Firstly, the temperatures of the textures were not measured or controlled, which can influence the perceived qualities of the materials. For instance, cold textures may be perceived as wet. Nonetheless, it should be noted that all materials were kept at room temperature throughout the experiments, resulting in minimal temperature variations. Secondly, the use of hand gel could have potentially affected the viscosity ratings. It is possible that the hand gel was unintentionally dispensed onto the textures, thereby introducing an external factor that could influence the results. Thirdly, no specific context was defined for the participants. Due to the display of white noise and the inability to visually perceive the texture, participants created their own context. This lack of context may have introduced variability in the responses and interpretations of the textures. However, a benefit of this controlled environment, was that the experiment was the same for each participant and could therefore be directly compared and external influences were kept to a minimum. Furthermore, the textures had to be placed inside the sleeve. As a consequence, the textures absorbed pressure, with the fabric of the sleeve already absorbing some pressure and the textures absorbing even more. Placing the textures directly on the McKibben muscles would have resulted in less pressure absorption, potentially affecting the haptic experience. Another limitation was encountered in the successful implementation of all textural properties within the sleeve. Imitating granular or viscose materials proved to be challenging for application in the sleeve, limiting the range of textures that could be effectively replicated. The sizing of the sleeve posed difficulties as well, as it did not accommodate all arm sizes. Thin arms faced challenges with correct tightening of the sleeve, while thick arms struggled with proper closure. This highlights the importance of considering variations in arm size when designing haptic devices. Moreover, it is possible that the check-all-that-apply list used to assess emotional responses did not optimally cover the range of emotions evoked by the studies. It was challenging to anticipate all possible emotions beforehand, leading to the potentially forgotten emotions or inclusion of redundant emotions in the list. This is mitigated by selecting emotional words that were validated in past research [18, 49] and covering a broad range of words from positive and negative extremes to more neutral emotions. Finally, the sample sizes of the first and the second study were relatively small, considering the wide variety of variables involved. Moreover, because three studies had to be performed in a short period of time, participants were mostly students or employees of the University of Twente and this probably compromised the generalizability of the data. To ensure sufficient statistical power, a larger sample size and a wide population distribution are recommended. Despite the limitations imposed, the results obtained do provide some valuable insights; however, definitive conclusions cannot be drawn based on these findings alone.

10 Conclusion

In this thesis, the affective response to various pressures and textures in passive touch has been explored. The focus of most research in the field of haptic devices has been on using vibration as stimuli, with little attention given to pressure as stimuli and even less to different textures. Additionally, among other things, pleasurable touch sensations favour maintaining and engaging relationships, such as parent-child and intimate romantic relationships. Besides human touch, previous studies had shown that haptic devices and soft textures can evoke pleasant tactile sensations. Background research revealed that the use of pressure in touch can evoke similar pleasurable emotional experiences as the classic social affective touch hypothesis related to C-tactile touch. Furthermore, recent research has shown that in active touch the perceived softness of a texture covaries with compliance, viscosity, granularity and furriness. A State of the art review found that little research has been done on the affective response of textures in haptic devices. Building upon this knowledge, the aim of this study was to gain new insights into the emotional experience of various pressures, the multiple dimensions of soft textures, and the resulting affective responses by using a haptic device. To achieve this, a total of three studies were conducted, where various stimuli were passively applied to the forearm using a haptic device called the McKibben Sleeve. The first study focused on exploring the multiple dimensions of soft textures in passive touch and selecting textures to be used in the third study. The second study investigated the affective response to different pressures, varying in force and duration. Finally, the third study examined the affective response to different textures identified in the first study.

The results of the first study validated a total of 17 textures for passive touch based on compliance, viscosity, granularity, furriness, and softness. The findings suggest an interlink between these material properties. Whereby it was observed that textures perceived as more compliant were experienced as softer and less rough. Additionally, the perception of furrier textures correlated with lower viscosity and higher compliance, while less granular textures were found to be more compliant. In the second study, it was found that increasing the pressure force led to an increase in participants' arousal responses. However, the pressure force did not have any effect on valence, and different durations had no impact on both valence and arousal. Lastly, the third study confirmed that softer textures were perceived as more pleasant, while harder textures were perceived as less pleasant. Furthermore, textures scoring high on furriness evoked calming sensations, whereas textures with high roughness ratings evoked irritating sensations. Moreover, textures that were difficult to rate on the material properties generally evoked neutral sensations.

These studies have provided new insights into the emotional experience of various pressures and the multiple dimensions of soft textures, as well as the affective responses they evoked. The findings indicate that different pressures and textures evoke distinct emotional responses. All in all, this research contributes to the fields of haptics and mediated social touch.

Although haptic technologies have not yet been extensively integrated into everyday life like visual and auditory technologies, this study represents a small step toward integrating haptics into daily experiences and inspiring further advancements. Overall, this study contributes towards enriching touch-based technology.

10.1 Future works

In order to further explore and expand upon the findings of this study, several directions and challenges for future research were identified. Firstly, it is recommended to investigate the effects of varying the force in combination with passively applying a texture. Additionally, exploring the impact of dynamic effects such as stroking or simulating a massage on the perception of textures could provide valuable insights. As past studies found that different dynamic effects evoked different emotions [5, 51, 55] and combining this with different textures could enhance its experience. Furthermore, testing the textures on different durations may reveal additional findings in tactile perception. Another area of interest for future work involves conducting active touch experiments using the identified textures and comparing the results with the findings of this study. This comparative analysis would shed light on the differences in perception and sensory responses between active and passive tactile interactions. Alternatively, expanding the study to include different body locations is also suggested. By exploring how the textures are perceived on various body parts, a more comprehensive understanding of the tactile experience can be obtained. One major challenge in future research is the difficulty to change a texture within wearables or haptic devices. Currently, applying different textures in a wearable device poses mechanical or chemical challenges. Exploring innovative solutions to this issue, such as developing materials with transformable chemical properties or mechanical adaptability, could greatly enhance the versatility and usability of wearable haptic devices. Another direction for future work is to incorporate a touch-giver device that can simulate mediated social touch. This addition would allow for a more realistic representation of touch experiences and can also help in giving context to the user, as opposed to the pre-programmed pressure stimuli used in the current study. Expanding the repertoire of textures for affective touch is another promising direction for future investigations. Including a wider range of textures would provide a more comprehensive understanding of the emotional responses evoked by different tactile stimuli. Lastly, future research should delve into the potential of textures as a medium for communicating emotions. It would be valuable to explore whether textures can effectively convey specific emotions and examine any potential overlap between the emotions evoked by textures and the emotions they are intended to represent.

By pursuing these future research directions, a more comprehensive understanding of tactile perception, its implications, and its potential applications can be achieved.

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A

Appendix

A.1 Material Stripplots

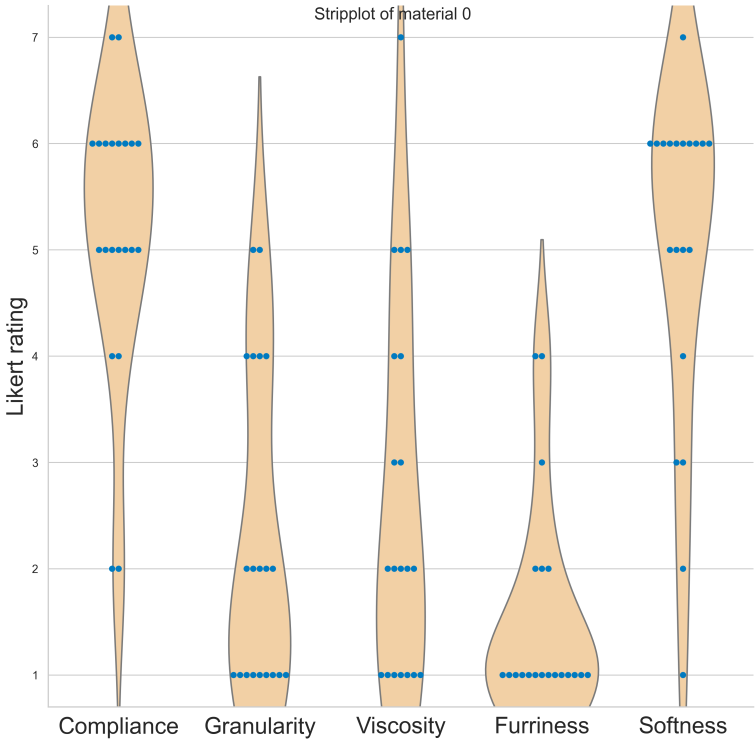

Figure 47: Stripplot of material: Sleeve

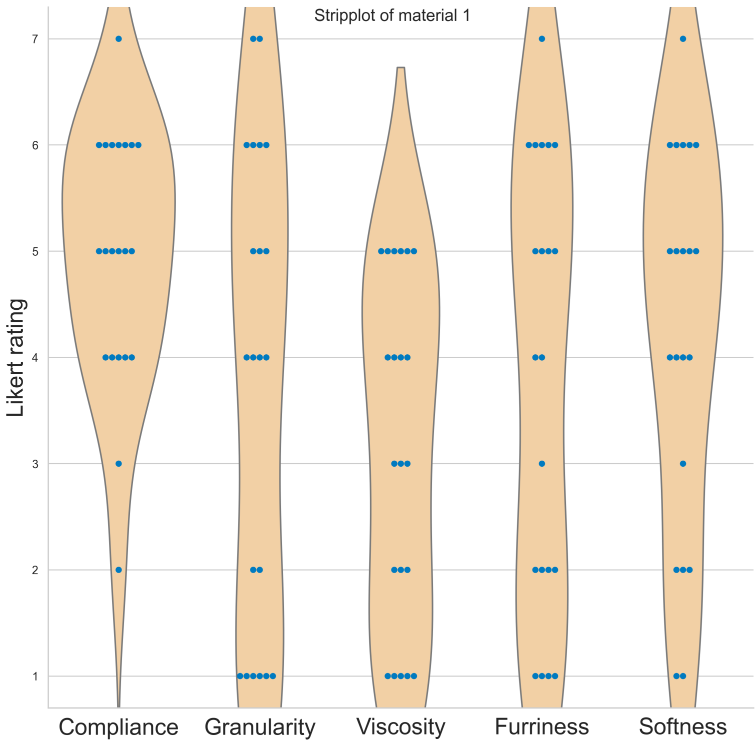

Figure 48: Stripplot of material: Bubble Foil

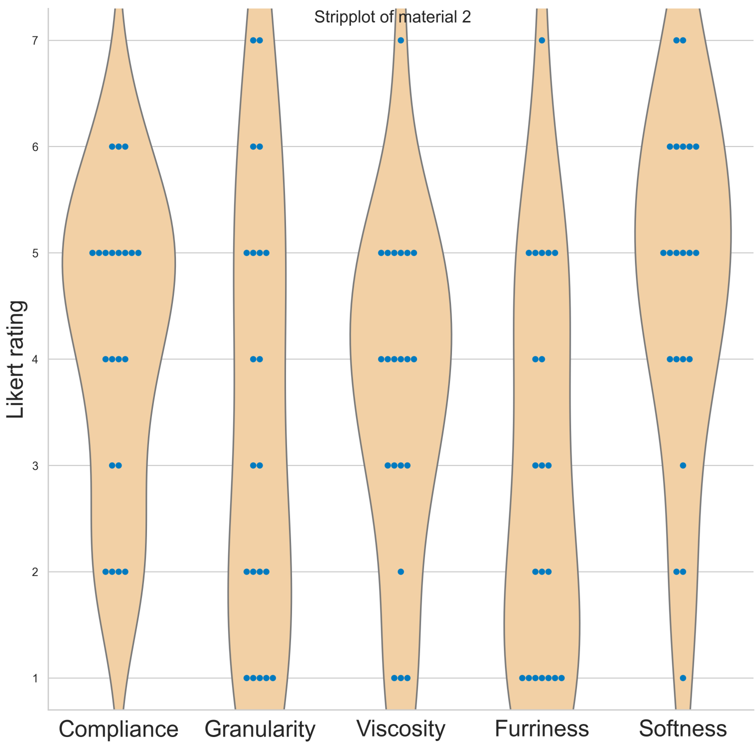

Figure 49: Stripplot of material: Rubber Mesh

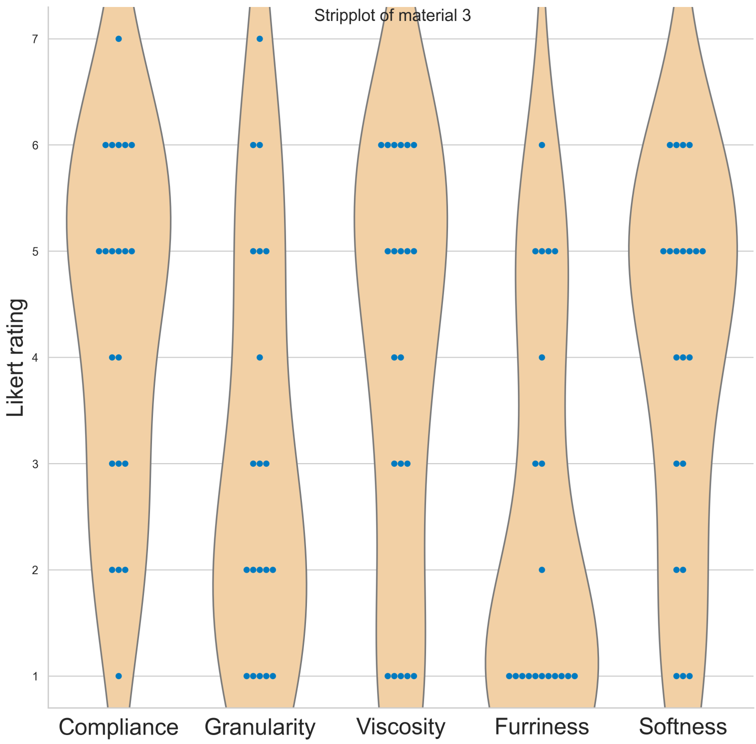

Figure 50: Stripplot of material: Pork Leather (4mm thick)

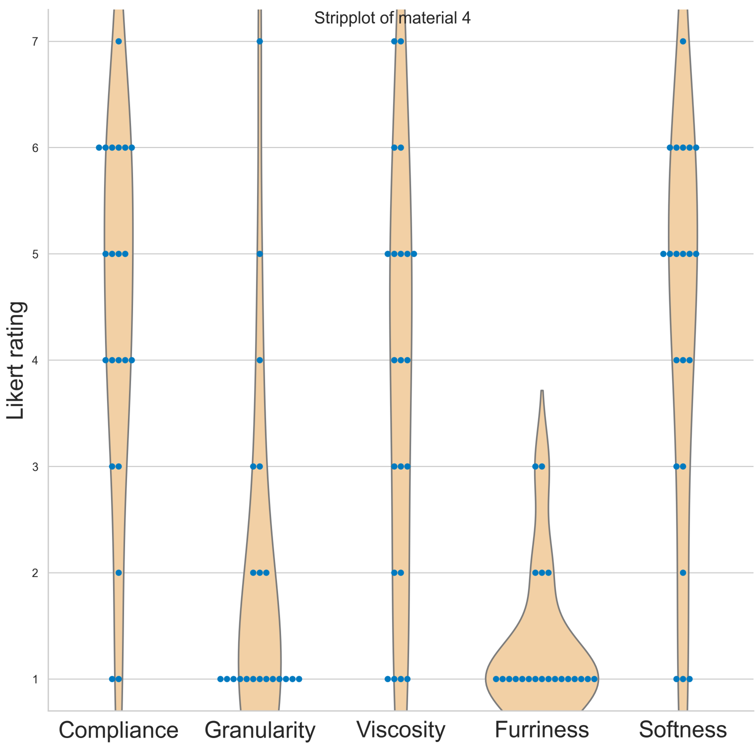

Figure 51: Stripplot of material: Pork Leather (2mm thick)

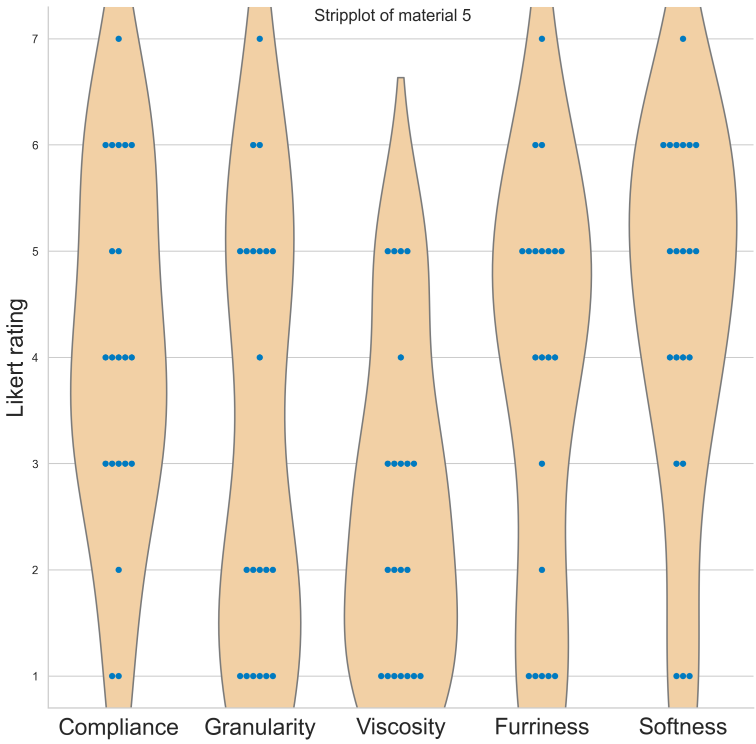

Figure 52: Stripplot of material: Organza

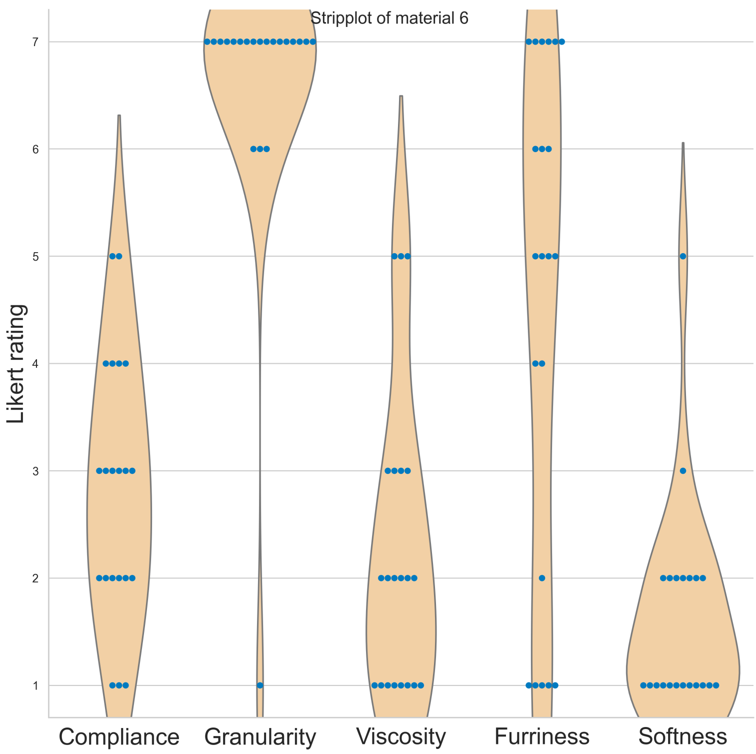

Figure 53: Stripplot of material: 3D Printed PLA

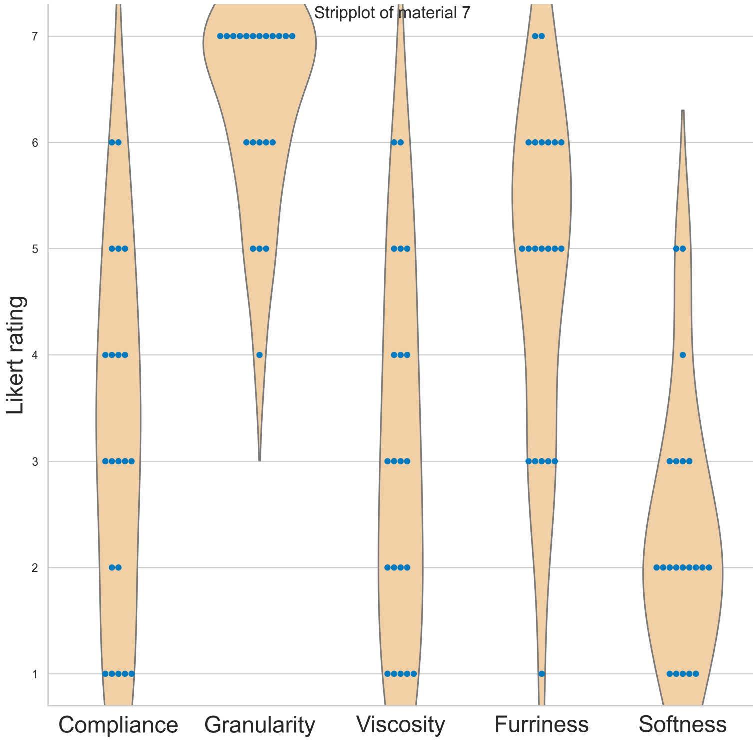

Figure 54: Stripplot of material: 3d Printed TPU

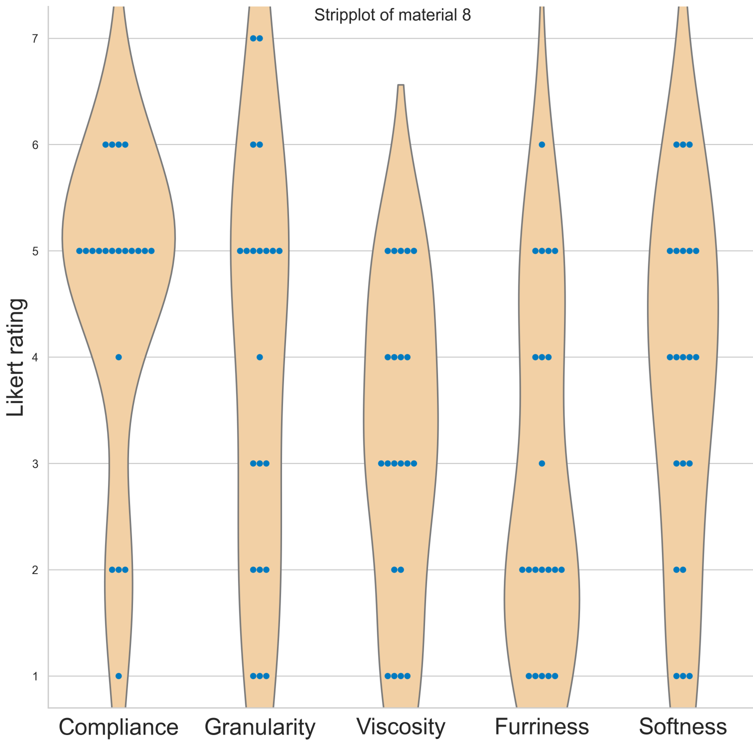

Figure 55: Stripplot of material: Hessian

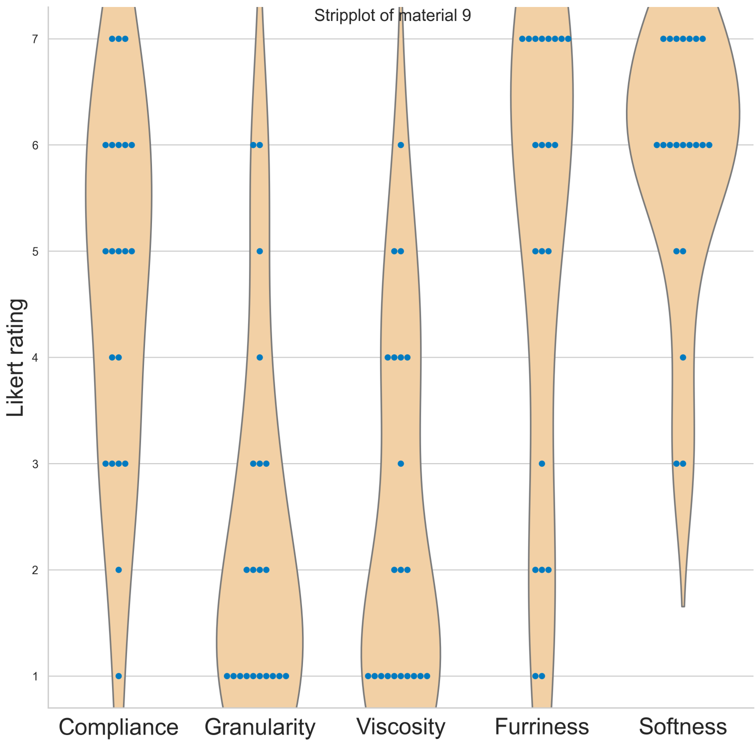

Figure 56: Stripplot of material: Fur Fabric

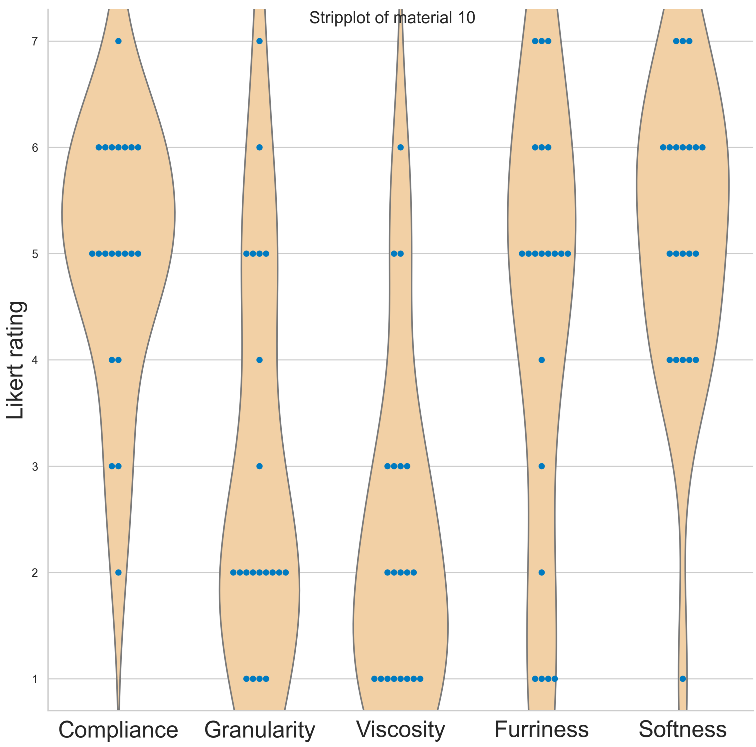

Figure 57: Stripplot of material: Modal Fabric

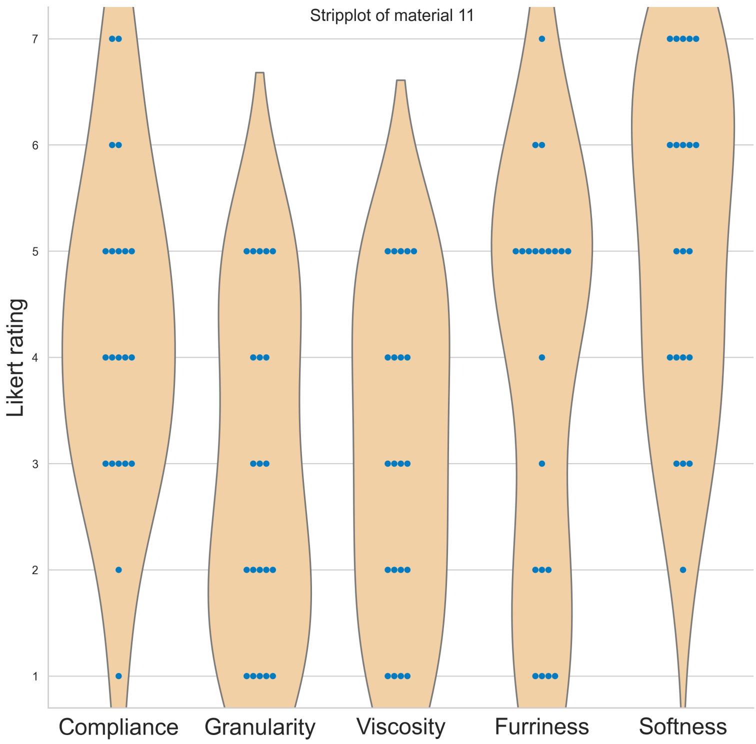

Figure 58: Stripplot of material: Velvet Fabric

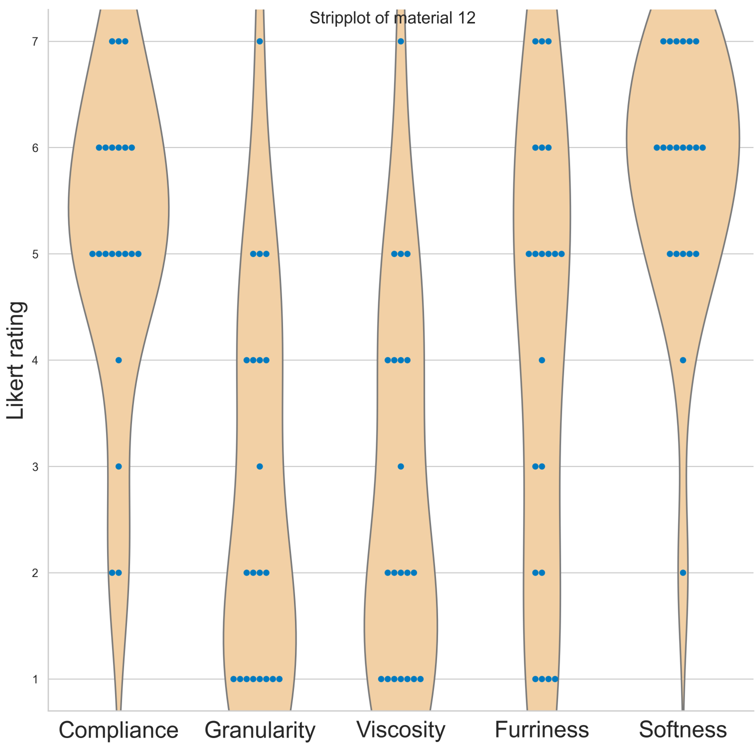

Figure 59: Stripplot of material: Polar Fabric

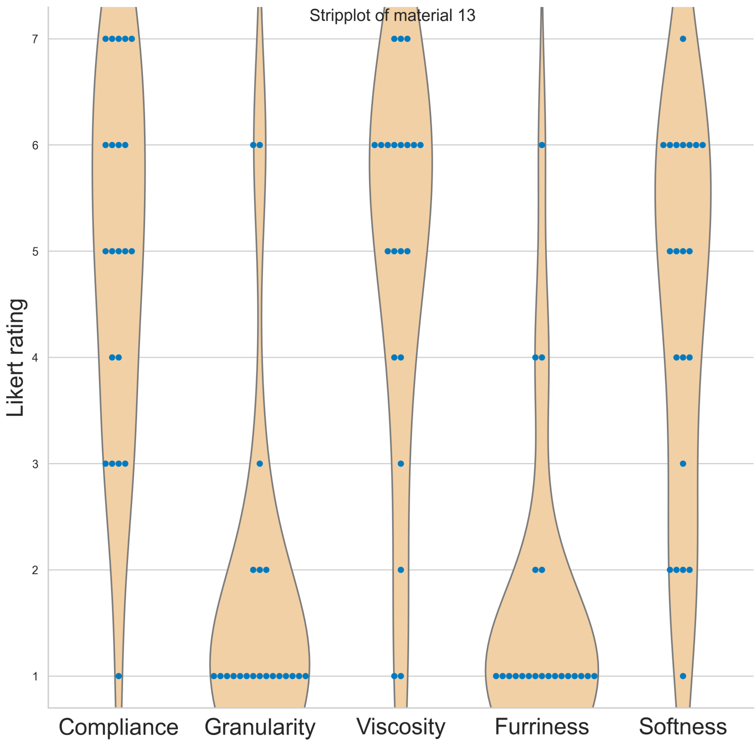

Figure 60: Stripplot of material: Slime

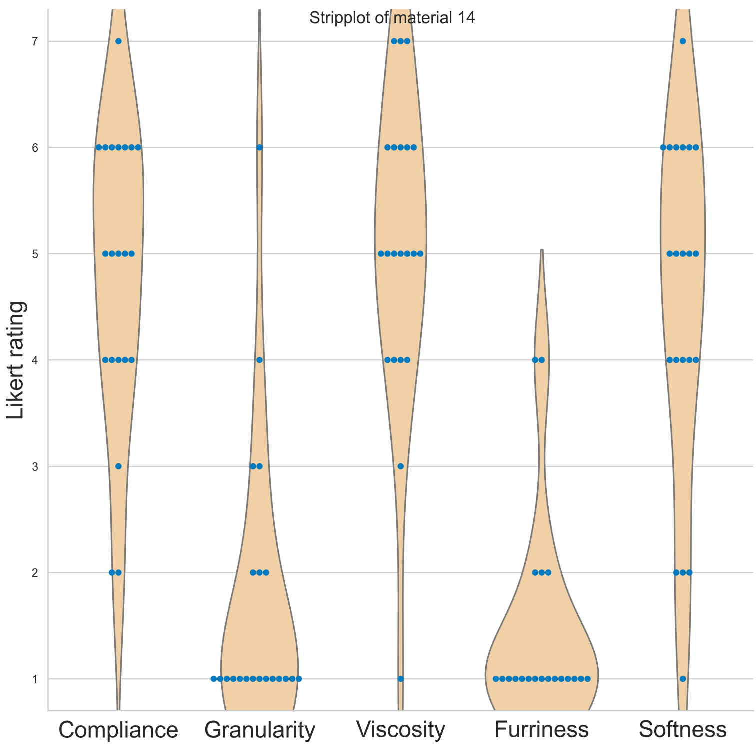

Figure 61: Stripplot of material: Humid Cleaning Wipes

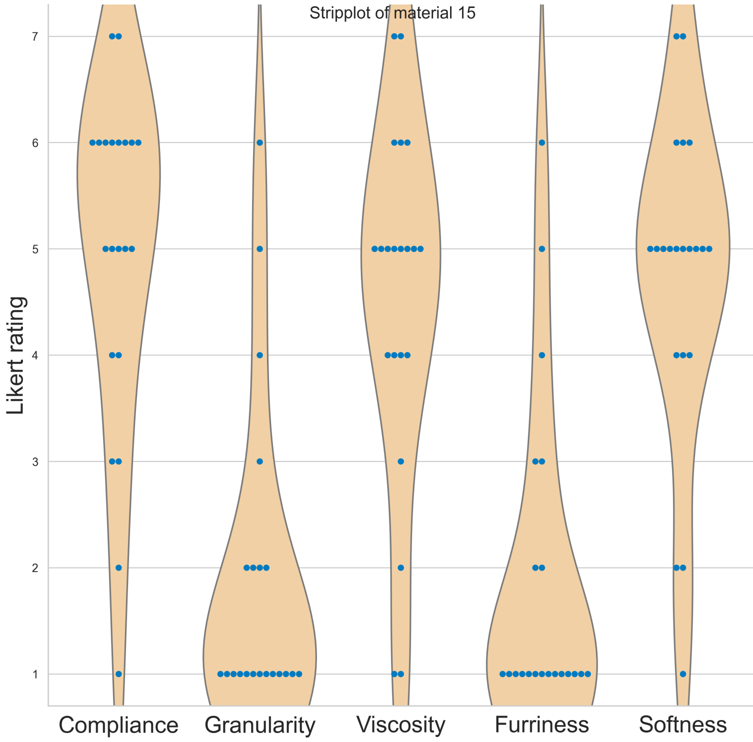

Figure 62: Stripplot of material: Latex Glove

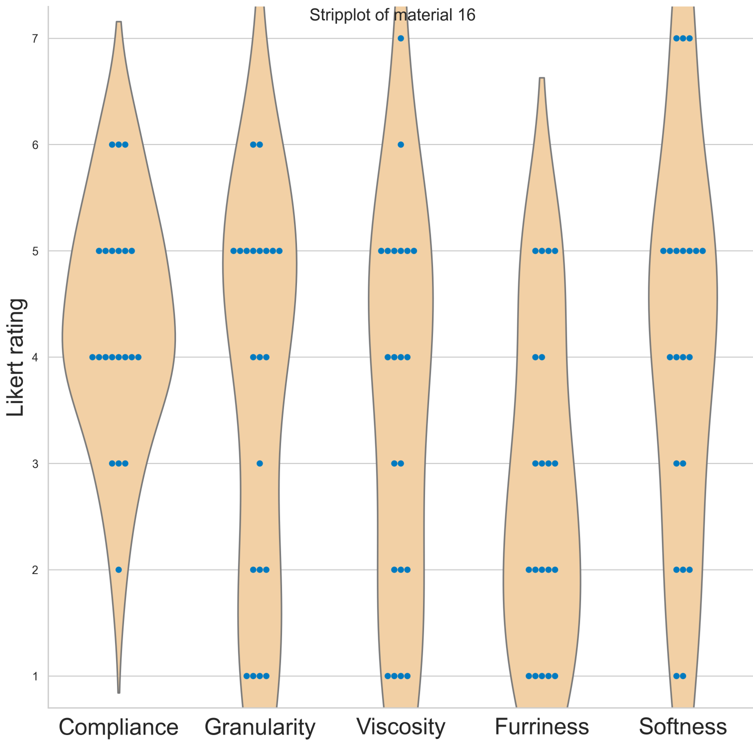

Figure 63: Stripplot of material: Aluminium Foil

A.2 Survey

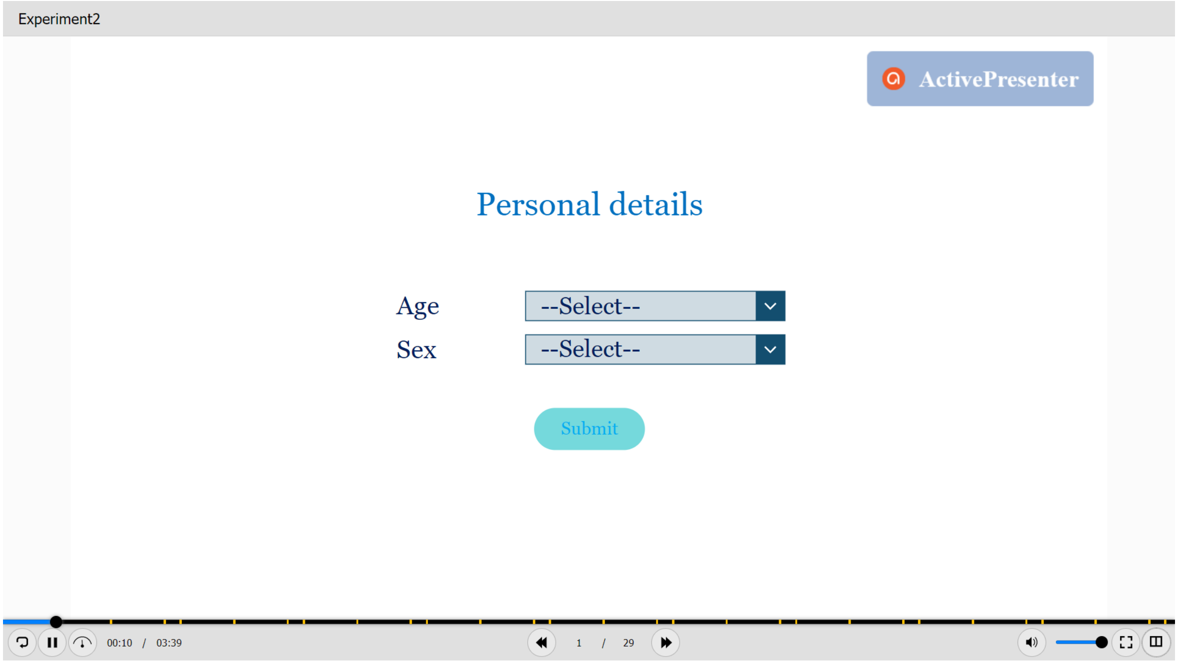

Figure 64: Personal Details

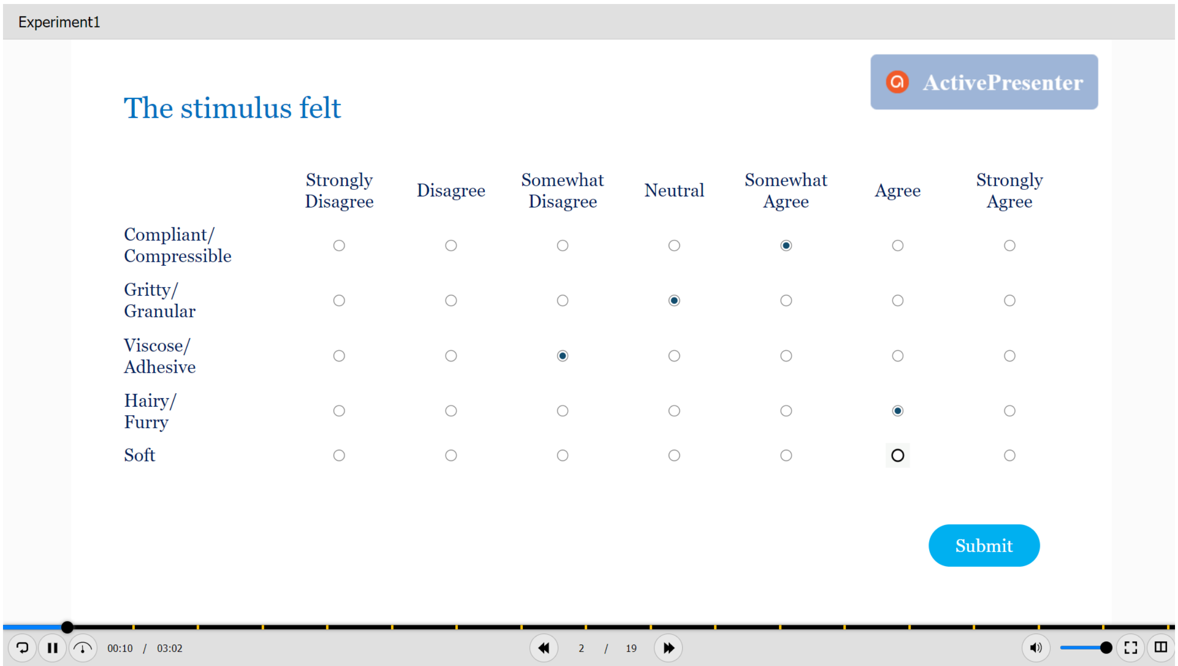

Figure 65: Likert question

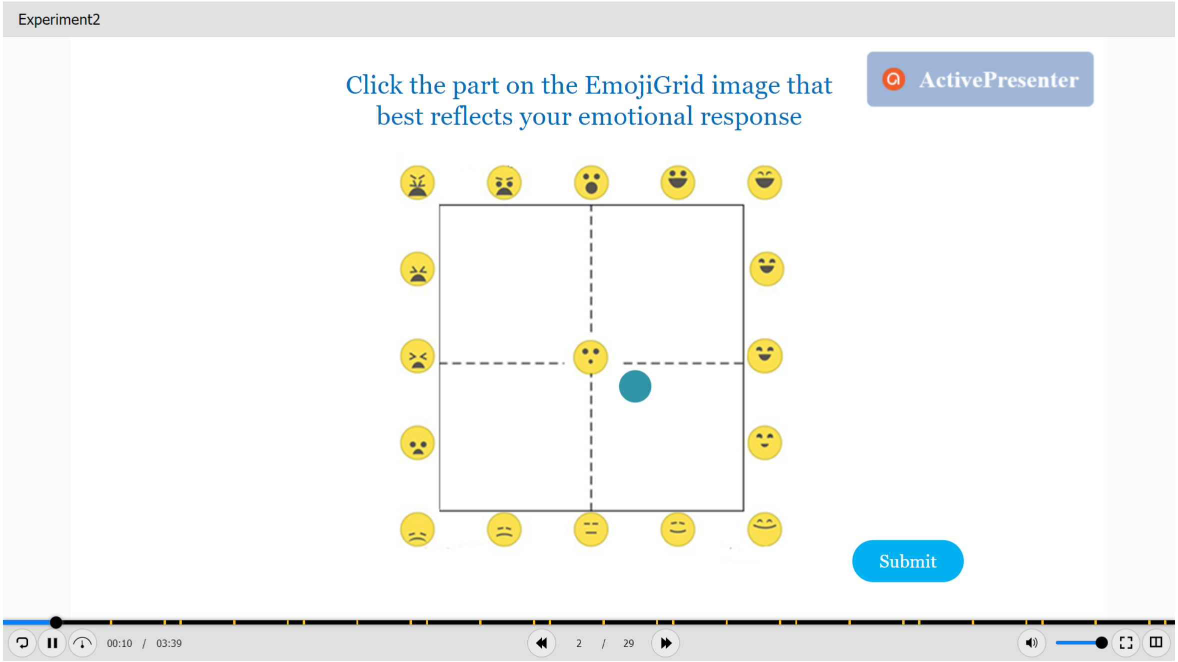

Figure 66: EmojiGrid

Figure 67: CATA-list

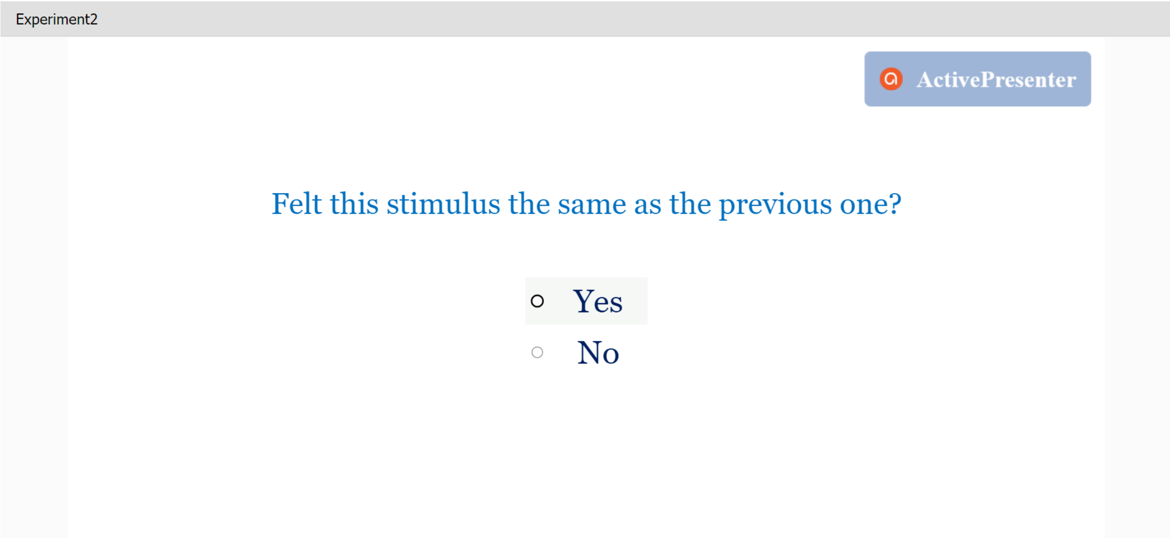

Figure 68: Yes/No question

A.3 Assumptions Study2

MANOVA Assumptions:

- The two dependent variables could be measured at the interval or ratio level.
- The independent variables consisted of two or more categorical, independent groups.
- There is independence of observations. Since there is no relationship between the observations in each group or between the groups themselves.
- The sample size is adequate namely 19.
- There is homogeneity of variance-covariance matrices. Levenes test p-value: 0.3885344167558794 > 0.05; Levenes test p-value: 0.14746952426029913 > 0.05. The homogeneity assumption of the variance is met.
- The multivariate normality assumption is not met as we accept the null hypothesis since the p-value is 0.0025105374086645538 which is way less than the alpha(0.05). Therefore it is not possible to perform a MANOVA on this data.
- There is a linear relationship between each pair of dependent variables for each group of the independent variable.
- There are no univariate or multivariate outliers as all calculated Mahalanobis distance p-values are below 0.001.
- There is no Multicollinearity as the multicollinearity assumption is met: VIF < 10, namely 4.409 < 10.

A.4 Assumptions Study3

MANOVA Assumptions:

- The two dependent variables could be measured at the interval or ratio level.
- The independent variables consisted of two or more categorical, independent groups.
- There is independence of observations. Since there is no relationship between the observations in each group or between the groups themselves.
- The sample size is adequate namely 19.
- There is homogeneity of variance-covariance matrices. Levene's test p-value: 0.8137873354628712 > 0.05; Levene's test p-value: 0.572972212743589 > 0.05. The homogeneity assumption of the variance is met.
- The multivariate normality assumption is met as we reject the null hypothesis since the p-value is 0.046670490763 08858 which is around the alpha(0.05) value.
- There is a linear relationship between each pair of dependent variables for each group of the independent variable.
- There are no univariate or multivariate outliers as all calculated Mahalanobis distance p-values are below 0.001.
- There is no Multicollinearity as the multicollinearity assumption is met: VIF < 10, namely 3.2970879177424286 < 10.

A.5 Smartwatch data graphs Study3

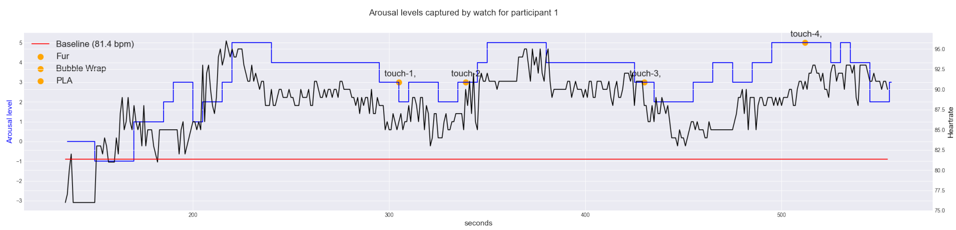

Figure 69: Arousal watch data graph of participant 1

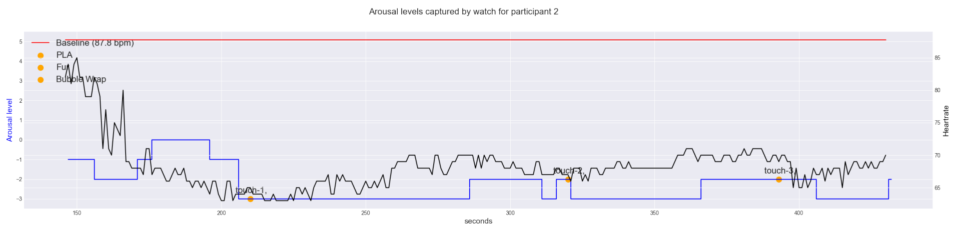

Figure 70: Arousal watch data graph of participant 2

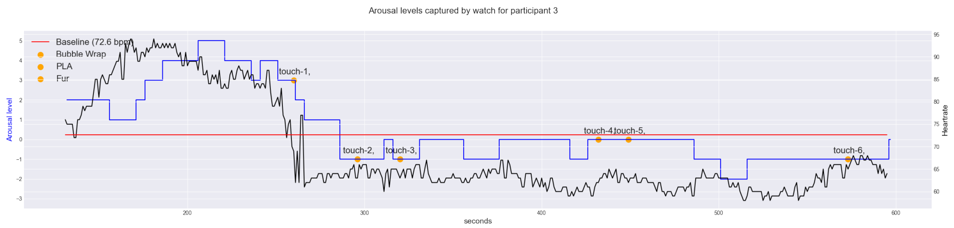

Figure 71: Arousal watch data graph of participant 3

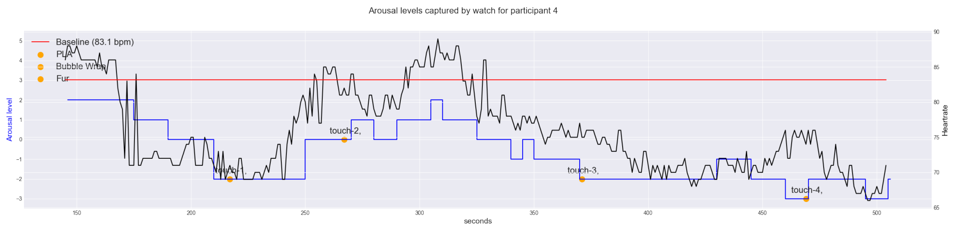

Figure 72: Arousal watch data graph of participant 4

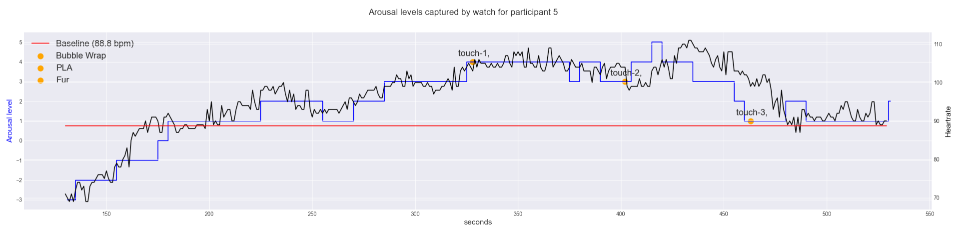

Figure 73: Arousal watch data graph of participant 5

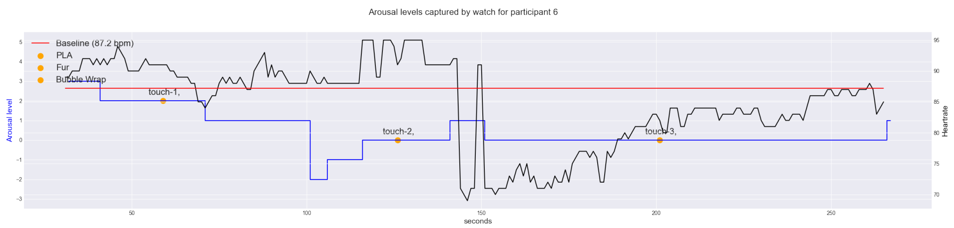

Figure 74: Arousal watch data graph of participant 6

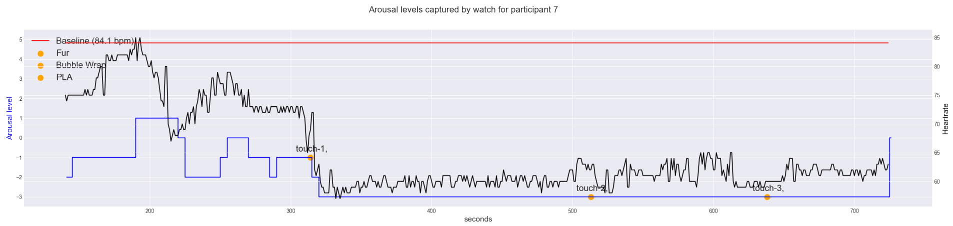

Figure 75: Arousal watch data graph of participant 7

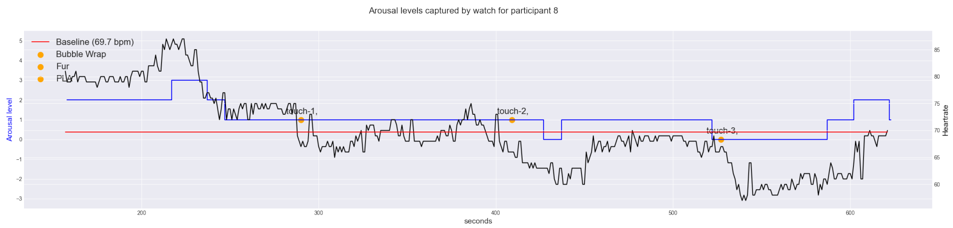

Figure 76: Arousal watch data graph of participant 8

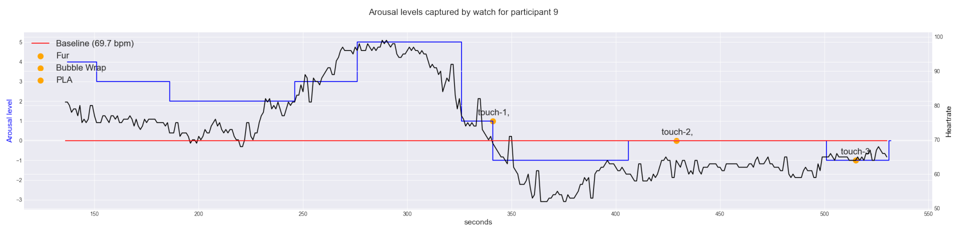

Figure 77: Arousal watch data graph of participant 9

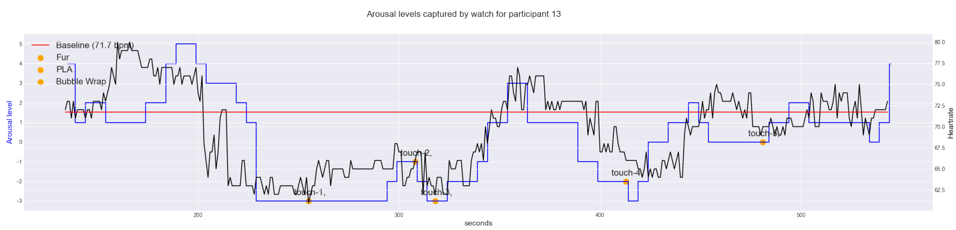

Figure 78: Arousal watch data graph of participant 13

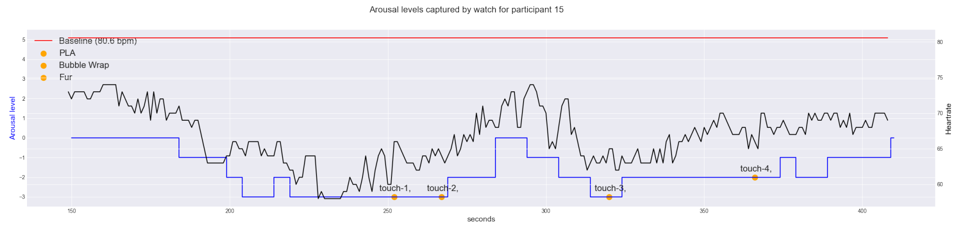

Figure 79: Arousal watch data graph of participant 15

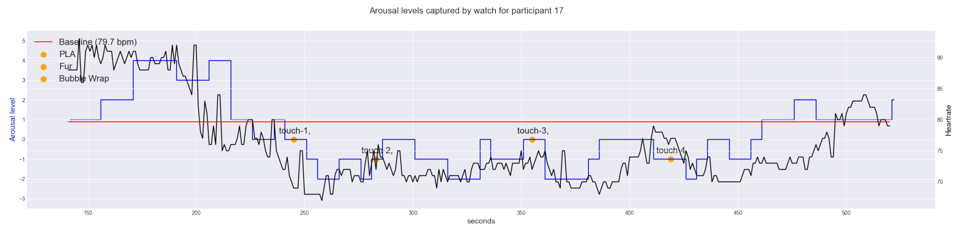

Figure 80: Arousal watch data graph of participant 17

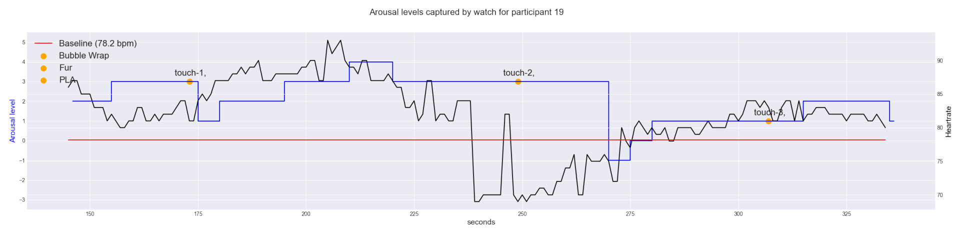

Figure 81: Arousal watch data graph of participant 19

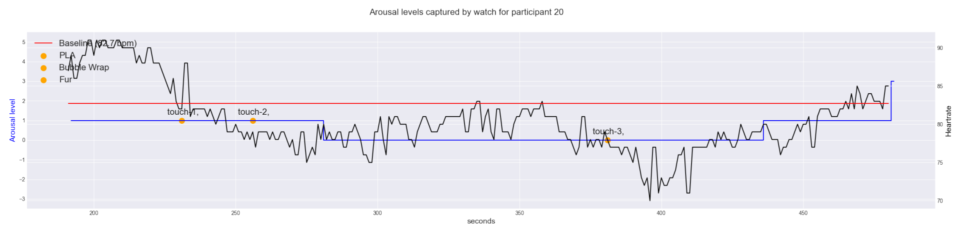

Figure 82: Arousal watch data graph of participant 20

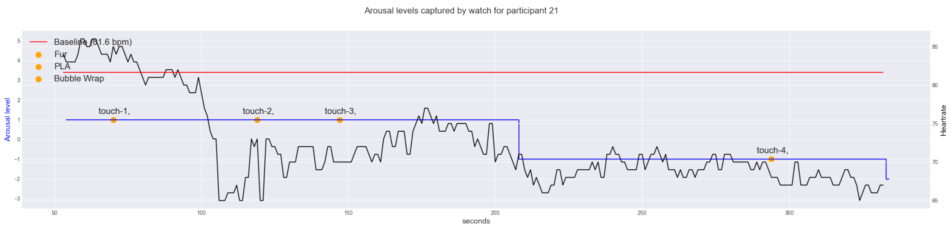

Figure 83: Arousal watch data graph of participant 21