

Perception Threshold for Pressure by a Soft Textile Actuator

Judith Weda, Angelika Mader, Hamid Souiri, Edwin Dertien and Jan van Erp

Abstract—Electroactive textile (EAT) has the potential to apply pressure stimuli to the skin, e.g. in the form of a squeeze on the arm. To present a perceivable haptic sensation we need to know the perception threshold for such stimuli. We designed a set-up based on motorized ribbons around the arm with five different widths (range 3 – 49 mm) for psychophysical studies. We investigated the perception threshold of force pressure and ribbon reduction in two studies, using two methods (PSI and 1up/3down staircase), comparing sex, the left and right arm, the lower and upper arm, and stimulated surface area with a total of 57 participants. We found that larger stimulation surfaces require less pressure to reach the perception threshold (0.151 N per cm² for 3 mm width, 0.00972 N per cm² for 49 mm width on the lower arm). This indicates a spatial summation effect for these pressure stimuli. We did not find significant differences in perception threshold for the left and right arm and, the upper and lower arm. Between male and female participants we found significant differences for two conditions (10 mm and 25 mm) in Experiment 1, but we could not reproduce this in Experiment 2.

Index Terms—haptic textile, electroactive textile, pressure, perception threshold, spatial summation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 825232.

I. INTRODUCTION

A wearable haptics designer's dream is to fully integrate lightweight, low-power, silent, and unobtrusive haptic actuators into a garment. This was suggested more than a decade ago [1]. Such a wearable haptic display has many applications, for example: mediated social touch, navigation for those who are visually impaired, or posture correction. Recent developments in the area of electroactive textile (EAT) bring the realization of such a display rapidly closer [2]–[4].

A. Electroactive textile and garment morphology

Depending on textile morphology, electroactive textile could present different haptic sensations. For example, whether a textile is woven, knit or when only certain parts of the textile construction are actuating yarns influences the haptic sensation in case of yarn actuation, much like these same qualities influence the passive sensation and experience of wearing a garment. One of the possible haptic sensations EAT could generate is pressure, the perpendicular force per unit area [5], by contracting the textile around the body part it is worn on, which can be implemented in wearable, haptic solutions for human computer interaction.

B. Pressure in touch interaction

Pressure is useful in varying types of touch interaction. For example, we use pressure to help identify objects when handling them by putting pressure on an object to figure out how hard it is or enclosing an object in our hand to find the global shape and volume [6]. The feedback we get about pressure on the fingers allows us to hold an object adjusting grip force based on the load force of the object and friction between the surface of the object and fingertips [7]. Pressure is a type of sensation also often felt and applied when engaged in social touch [8, 3.3.2], for example when hugging another person, holding hands or performing a handshake.

Social touch is key to our relationships and mental well-being. Social touch between humans can positively influence the development of infants [9] and the health and well-being of the elderly [10].

In a social setting it is common to touch the arm, e.g., with a hug. The arm is also an acceptable area of touch for all levels of familiar relationships [11]. Creating pressure on different body parts with a wearable would enrich and enhance the experience of mediated social touch applications.

The benefit of pressure touch on the arm is supported by products such as the 'Hey bracelet'. The 'Hey bracelet' allows users to send a touch to each other. The touch is created by the bracelet contracting around the user's wrist, creating a pressure sensation [12].

Other related work includes devices created as a research effort. In [13] the author names a number of research projects where pressure was the core stimulus of the haptic experience generated by their mediated social touch device. An early example utilising pressure is the 'huggy pajama'. A pyjama that inflates and creates warmth when a parent hugs their child at a distance [14]. In [15] the authors created a squeezing device for mediated social touch and found that it increased connectedness in their storytelling setting. Other possible applications include alerts, navigation and abstract representation of information.

The previous efforts and findings indicate that pressure has a definite place as a modality in mediated social touch. The current devices are limited in wearability due to multiple reasons, for a number of devices bulkiness is one of the reasons [16], [17]. This limits application in daily life. This is where EAT has a benefit, as it is integrated into the textile and therefore as wearable as any garment, only needing a small control unit and battery in addition to create a sensation of pressure on the skin.

C. Skin and mechanoreceptors

Properties of the skin, for example skin thickness, can differ between sexes and age groups [18]. In addition, differences in sensitivity between sexes have been found as well, for example females have lower thresholds for two-point discrimination [19].

Humans have both glabrous and hairy skin. Both types of skin have different functions and have different mechanoreceptors. The glabrous skin can be found on the hands and is used to explore our environment and objects [20].

The hairy skin is the skin on the rest of the body. These body locations like arms or back are locations where we often receive social touch. These locations are less sensitive than the glabrous skin locations [21].

There are different kinds of mechanoreceptors with varying parameters regarding sensitivity to types of touch, an overview can be found in table I. Meissners corpuscle respond to light touch, Ruffini endings respond to skin stretch and directional force, Merkel discs respond to pressure. The latter two are slowly adapting and are able to record sustained pressure. [22] found that the size of SAII units receptive fields increased with indentation force. Another finding is that the receptive fields of the rapidly adaptive mechanoreceptors in the hairy skin of the forearm (volar side and sides) were larger than the receptive fields of the same mechanoreceptors on the face. In addition, more evidence was presented and [22] concluded that the hairy skin on the forearm is different from hairy skin on the face and back of the hand. Thus, not all hairy skin is the same and different body parts need to be studied.

Aside from the mechanoreceptors in table I the hairy skin has an additional, separate system for touch, namely the CT-afferents [23]. This separate system is specifically sensitive to affective touch, namely stroking at a rate between 1 and 10 cm per second [24]. Multiple pressure stimuli can also generate the feeling of a stroke. [16] created a pneumatic sleeve with several segments that, when inflating sequentially, create the sense of a stroke using the apparent motion illusion. [25] found that touches on different hairy locations (cheek, arm) evoke a more affective assessment of the stimulus than on the palm.

D. Research gap

There is some existing research about pressure stimuli, but as far as the authors are aware, there is no psychophysical research into pressure by textiles. Since Electro-active textile is an actuating textile that can present pressure on the skin, there is a need to study the desired perceptual aspects of this technology. This includes psychophysical studies of threshold, spatial and temporal resolution, and perceptual illusions. The timeliness of these studies is relevant, as psychophysical data can guide the development of EAT and the garments and applications developed with EAT. Therefore, we started investigations by simulating the haptic stimuli that EAT are expected to produce with a substitute technology, a motorized ribbon. This motorized, satin woven ribbon does not stretch, can fold along the arm and is capable of a contraction movement mimicking the expected properties of the EAT.

In this paper we investigate the perception threshold of pressure using a motorized ribbon. This substitute can simulate the material and actuation qualities of future EAT. With the results, we can guide the development of EAT in the direction of a haptic actuator capable of providing perceivable pressure stimuli. In section 2 we describe the motorized ribbon, set-up and model, followed by Experiment 1 in section 3 and Experiment 2 in section 4. In section 5 we discuss our results.

II. DEVICE, SET-UP AND MODEL

The goal of the motorized ribbon device is to present pressure by textile on the arm for psychophysics experiments. This is achieved by contracting a ribbon around a section of the human arm that is placed in resting position on a desk or table. The setup has been made flat with a concave arm rest and cushions, so the arm can rest comfortably. While it is possible to move the arm slightly while in the set-up, participants are asked to not move their arm. The device will correctly measure the pressure even if the arm is moved slightly. To focus on the pressure stimulus, it is important that no other visual cues, vibrations or sounds are generated by the device. Figure 1 shows a participant comfortably with their arm placed in the device, which is visually separated from them by a screen, vibrations are dampened within the device and are further cancelled by a rubber mat, sound is blocked by noise-cancelling headphones playing white noise.

1) *Physical system:* The device is shown in figure 2, in the version used in the experiment the cables are shielded to prevent noise. It has a total height of 28 mm and easily fits on a table or desk. The setup consists of a large acrylic baseplate of 400x300mm with aluminum extrusion frames on the edges.

In figure 2 we see that one side of the ribbon (D) is connected to a rod (G) attached to a thread which is passed through the end of the linear servo-motor (A) and finally connected to a load-cell (B1) which is mounted on the frame. The other side of the ribbon is attached to the linear spring (F), the spring is attached to a load cell (B2) on the opposite side. The ribbon is tightened using a linear motor, which pushes the tendon (C) tied to the ribbon between two vertical rollers. By measuring the contraction force at two ends, the effects of friction and motor dynamics can be measured and cancelled out. The ribbon is wrapped around a segment of the human arm on a 3D printed armrest (G), which holds two rods in ball bearings to reduce the amount of friction and lateral forces on the skin.

The spring acts as over-strain protection to protect both load cells. The deflection under force is small compared with the applied range, and eventually the goal is to apply a force and not measure position change as such. Also, given this spring, the servo motor acts as a series-elastic actuator, meaning that the deflection of the servo motor is acting as a force actuator with an output force of the spring constant $1.18 \text{ N} / 2$ times the servo extension. Also, small movements by the test subject's arm are compensated by this spring, not to damage the setup.

We found some issues with the device during Experiment 1 which were fixed before running Experiment 2. One of the load cells did not always return to zero after force was released.



Fig. 1. Top: A participant with their arm in the motorized ribbon device. Middle: A cross-section of the set-up with an arm. The figure shows the linear motor (A), load cells (B), Tendon (C), Ribbon (D), Rod (E), Spring (F). Bottom: The ribbons in relation to the arm. The broadest ribbon (49 mm) is the most transparent, decreasing in transparency are the 25 mm, 15 mm, 10 mm and 3 mm ribbons. Finally, there is a line indicating the middle of the arm.

This issue of remaining forces was fixed with a thorough cleaning of the device and reoccurring use of "WD-40 Multi-Use Product" before each session.

2) *Control*: As a control interface a generic microcontroller (Arduino Uno) is attached to the linear servo motor (L12 series by Actuatorix, with a stroke of 50 mm and 1:100 gear ratio, 12 mm/s speed and peak power of 23 N). A single motor step is equal to 0.5 mm. Both load cells (strain gauge based, CZL-635, 0-5 kg) are connected to the same microcontroller using two identical INA122 instrumentation amplifiers with a gain set at 2000.

With an Arduino sketch, a calibration procedure is initiated for each experiment, setting the applied force to zero before strapping a test subject in. Several software applications have been developed to perform different experiments in both Pro-

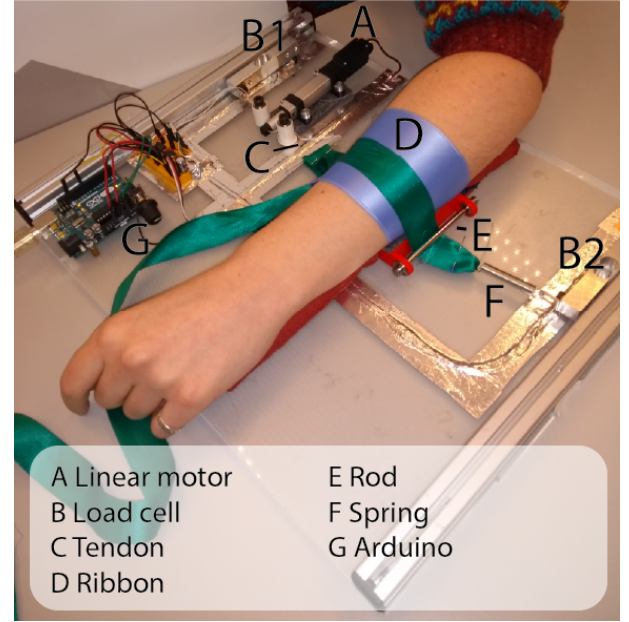


Fig. 2. Motorized ribbon device for psychophysics experiment. The figure shows the linear motor (A), load cells (B1,B2), Tendon (C), Ribbon (D), Rod (E), Spring (F) and Arduino (H)

cessing (v3.5.4) [26] and PsychoPy (v3.0) [27]. The software applications control the motor by setting motor steps. Start position and motor position at the moment of strapping in the arm of the participant is always at motor step 50.

3) *Model*: We measure the forces in Newton on both sides of the ribbon with load cells. We used equations based on the capstan principle to determine the normal force (F_n), friction forces (F_f) and friction coefficient (μ) on the arm. The capstan principle relates the hold force or tension on the ends of a rope or similar to the load force on the cylinder it is wrapped around. The relation is further explained in the equations 1, 2, 3, where T_l is the tension as measured by load cell B2, T_r is the tension as measured by load cell B1 and delta theta is the length of the contact area of the ribbon on the arm in radians:

$$F_n = (T_l + T_r) \times d\theta/2 \quad (1)$$

$$F_f = T_l - T_r \quad (2)$$

$$\mu = F_f / F_n \quad (3)$$

We assume that there is negligible friction and that the arm is a perfect cylinder. For the first experiment, we used a cylinder with a circumference of 22.5 cm to determine delta theta (2.88 radians) and used this value for all participants. In the second experiment, we investigated the upper and lower arm which differ substantially in circumference. Therefore, we determined that delta theta specifically for each arm circumference. To that end, we 3D-printed cylinders of different circumferences and placed them in the device to find the length of the contact area in arc degrees by marking where the ribbon touches the cylinder and using a protractor. The measured arc degrees were converted to radians to be used as delta theta in

the formula. The results of this exercise can be found in table I.

TABLE I

LENGTH OF THE CONTACT AREA OF THE RIBBON ON THE ARM IN DEGREES PER ARM CIRCUMFERENCE FOUND BY PLACING 3D-PRINTED CYLINDERS OF DIFFERENT SIZES IN THE DEVICE, MARKING THEM AND USING A PROTRACTOR. THIS TABLE WAS PUBLISHED EARLIER IN [28].

Circumference in cm	Arc length of contact area in degrees	Arc length of contact area in radians
18	141	2.46
19	150	2.62
20	153	2.67
21	155	2.70
22	162	2.83
23	171	2.98
24	175	3.05
25	180	3.14
26	190	3.32
27	197	3.44
28	197	3.44
29	198	3.46
30	202	3.53
31	219	3.82
32	222	3.87
33	223	3.89
34	223	3.89
36	229	4.00

To find the force per square cm we simply divided the normal force (F_n) by the total arm surface touched by the ribbon, which is the ribbon width times the length of the contact area in cm.

III. EXPERIMENT 1

The goal of experiment one was to find the perception threshold of a pressure stimulus by a satin ribbon on the arm and to find if there were differences between the left and right arm, ribbon width and sex.

A. Method

1) *Participants*: Participants were all working or studying at the University of Twente or acquainted with the researchers, 8 male and 7 female in total. Aged 18 to 42 years (mean = 24.39, median = 24, SD = 2.76). Two were left-handed and 13 were right-handed.

2) *Procedure*: A non-moving, satin ribbon (72 mm) with a width exceeding that of the motorized ribbon was placed around the arm to reduce friction between the arm and the ribbon that is pulled. Then, we determined the middle of the lower arm by measuring the length from the wrist bone to the elbow and marked it. The lower arm was in the device so that the middle was lined up with the middle of the motorized ribbon. We tested 3 different ribbon widths, a small ribbon of 10 mm, a medium ribbon of 15 mm, and a large ribbon of 25 mm. Participants were presented with a stimulus before the experiment started to get familiar with the sensation. They wore active noise-cancelling headphones that played white noise to remove auditory cues and were seated in a cubicle. Room temperature was between 18.8 and 24.4 degrees Celsius. Covid-19 guidelines were in place and adhered to. Participants

TABLE II
THE AVERAGE PERCEPTION THRESHOLD OF FORCE FOR THE LEFT AND RIGHT ARM.

Left arm					Right arm			
Width	N	Mean	Median	SD	N	Mean	Median	SD
10	11	0.41	0.35	0.15	11	0.59	0.35	0.52
15	11	0.4	0.37	0.21	11	0.56	0.43	0.38
25	11	0.57	0.51	0.28	11	0.59	0.54	0.3

TABLE III
THE AVERAGE PERCEPTION THRESHOLD OF N PER SQUARE CM FOR THE LEFT AND RIGHT ARM.

Left arm					Right arm			
Width	N	Mean	Median	SD	N	Mean	Median	SD
10	11	0.04	0.034	0.01	11	0.06	0.04	0.05
15	11	0.03	0.02	0.01	11	0.04	0.03	0.03
25	11	0.02	0.02	0.01	11	0.02	0.02	0.01

TABLE IV
THE AVERAGE REDUCTION OF THE RIBBON OR CHANGE IN POSITION FROM THE START FOR THE LEFT AND RIGHT ARM.

Left arm					Right arm			
Width	N	Mean	Median	SD	N	Mean	Median	SD
10	11	64.4	63.8	3.97	11	61.5	62.1	5.85
15	11	59.6	59.3	2.79	11	61.1	61.7	5.31
25	11	61.1	61.7	6.42	11	61.6	58.7	8.58

TABLE V
THE AVERAGE PERCEPTION THRESHOLD FORCE PER SEX.

Female					Male			
Width	N	Mean	Median	SD	N	Mean	Median	SD
10	6	0.53	0.39	0.34	7	0.46	0.40	0.17
15	7	0.49	0.45	0.21	7	0.57	0.42	0.35
25	7	0.60	0.61	0.16	7	0.60	0.57	0.27

TABLE VI
THE AVERAGE PERCEPTION THRESHOLD OF PRESSURE PER SEX.

Female					Male			
Width	N	Mean	Median	SD	N	Mean	Median	SD
10	6	0.05	0.04	0.03	7	0.05	0.04	0.02
15	7	0.04	0.03	0.01	8	0.05	0.03	0.05
25	7	0.03	0.02	0.01	8	0.03	0.02	0.03

TABLE VII
THE AVERAGE PERCEPTION THRESHOLD OF RIBBON LENGTH REDUCTION PER SEX.

Female					Male			
Width	N	Mean	Median	SD	N	Mean	Median	SD
10	6	60.4	61.3	2.55	8	68.9	70.0	5.22
15	7	59.6	60.2	2.34	8	64.5	64.5	4.5
25	7	58.5	58.2	4.57	8	67.3	67	5.53

were asked to join for two separate sessions on separate days for the left and right arm. The research and Covid-19 procedures were reviewed and approved by the ethics committee of the EEMCS faculty of the University of Twente under number RP 2020-105.

3) *Measures*: The measures for this study are basic demographics (age, gender and dominant hand), the arm circumference of the participant, the ribbon width, the motor step, the ribbon reduction, the forces measured by the two load cells in the device and the yes/no answers from the participants. The ribbon reduction is deduced from the motor step. The motor

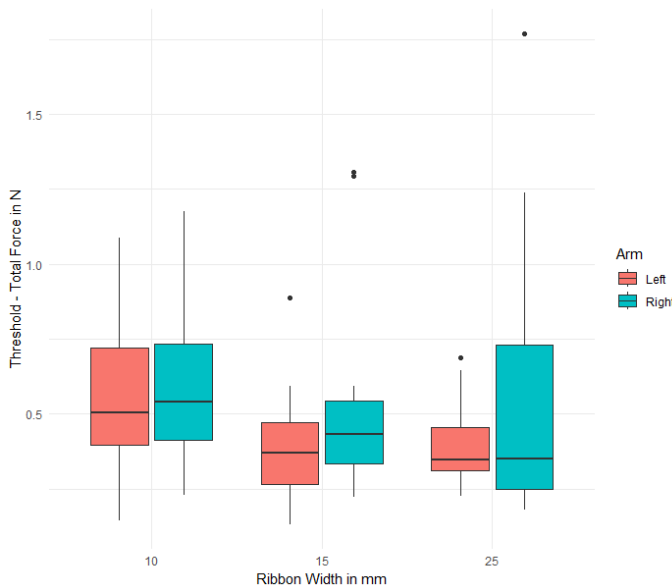


Fig. 3. The force threshold of the three ribbon conditions (10 mm, 15 mm, 25 mm) for the left and right arm. The dots indicate individual participants, the colours the left and right arm, the lines above the boxplots are accompanied by significant p-values found when comparing the conditions. The box plots follow standard Tukey representations. The middle bar indicates the median. The lower edge of the box is the 25th percentile and the upper edge is the 75th percentile.

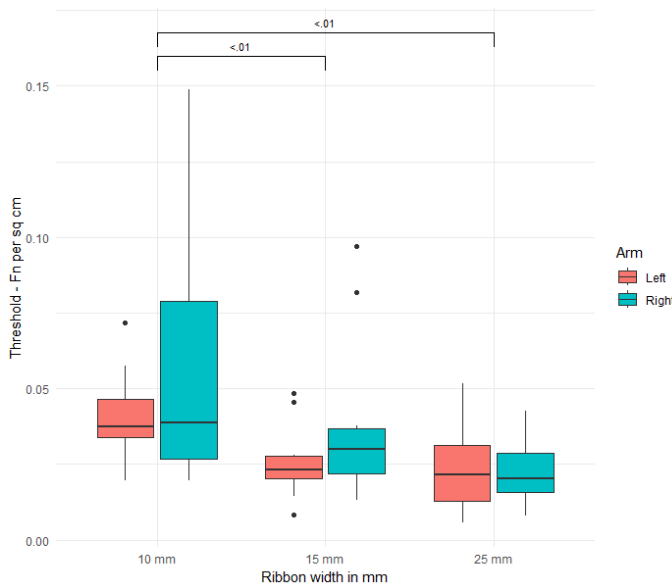


Fig. 4. The perception threshold in terms of pressure for the left and right arm. The dots indicate individual participants, the colours the left and right arm, the lines above the boxplots are accompanied by significant p-values found when comparing the conditions. The box plots follow standard Tukey representations. The middle bar indicates the median. The lower edge of the box is the 25th percentile and the upper edge is the 75th percentile.

pushes the tendon attached to the ribbon past two bearings. They have a linear relationship, each motor step causes a reduction of 1 mm.

4) *Psychophysical method:* We used a 1 up/3 down staircase, with a step size of 5 based on the steps of the motor, with 7 reversals for each arm (left and right) and ribbon

width (10,15,25) [29]. Participants participated in both an upwards and a downwards staircase for each ribbon width. The staircase method is an adaptive psychophysical method. The answers of the participant determine the next stimulus. The participants answered the following questions: "Do you feel pressure?". In a 1 up/3 down staircase a participant has to answer correct, indicating they feel the stimulus, three times before the stimulus is lowered according to the step size, after one incorrect answer, indicating they did not feel the stimulus, the next stimulus is increased according to the step size. This 1 up/3 down rule targets 79.37 percent correct rate [30].

5) *Analytic strategy:* We used the default logistic function of quickpsy [31] and to the more common t_{75} (i.e. the threshold where 75 percent of the stimuli are detected) for our data rather than the 79.37 percent correct rate. We used a t-test to compare between sexes. For data that was not normally distributed we used a Wilcoxon rank sum test. To compare between ribbon widths and the left and right arm we used a two-way repeated measures ANOVA. Where appropriate, Bonferroni adjusted post-hoc tests were applied.

B. Results

1) *Data inspection and cleaning:* Before analyzing the results, some data were removed. The data of participant 4 was retracted after data collection was finished and thus removed from the final data set.

The left-hand session of a participant was removed from the data as the string attaching the ribbon to the motor broke. The first part of the session with another participant was removed, as the new string got wedged in the guiding pulleys multiple times. The right arm session for a third participant was removed before analysis on account of a gaming injury on that arm.

Two force thresholds stood out from the data. For the first the threshold was 236 N and for the second the threshold was negative. Both these values are not reliable since 236 N is far larger than the forces we applied (0 N - 5 N) and a threshold below a force of 0 N is not meaningful. We examined the individual data points for each participant in this situation before fitting the data. For the first we found that two data points were a lot higher than the other data points (5 N vs. all other points below 1 N) these were removed, and the fit resulted in a normal threshold. For the latter, we found some obvious incorrect answers. The participant indicated not feeling the stimulus at high forces of 1.4 and 3.6 N. These data points were removed, and the fit resulted in a normal threshold.

The change of the motor position how much the ribbon length reduced around the arm in mm and can be an indirect measure of skin indentation. Six thresholds stood out. They were negative or impossibly high. Upon further investigation the odd thresholds came from the upwards staircases. For these six cases the data from the upwards staircase was removed.

Thresholds that were outliers of more than 3 times the SD from the mean were removed from the data set.

2) *Comparison of the threshold force between ribbon widths on arm on the left and right arm:* First, we checked

if there was a difference between the right and left arm and the ribbon widths. To make this comparison, only the data of participants that participated for both a left and right arm session was used.

We calculated the means, see table II and figure 3. We ran a two-way repeated measures ANOVA for the arm (left/right) and ribbon width. The data passes Mauchly's test for sphericity (p -value $> .05$) and the Shapiro-wilk test for normality ($p > .05$). We found no significant difference for the interaction ($F(2, 20) = 0.81$, $p = 0.46$) and simple main effects analysis showed no significant difference for arm ($F(1,10) = 1.56$, $p = 0.24$) and ribbon width ($F(2,20) = 1.12$, $p = 0.35$).

3) *Comparisons of threshold for pressure between ribbon widths on the left and right arm:* As broader ribbons cover a larger surface area of the arm than slimmer ribbons, we also determined the perception threshold of the force in relation to the covered skin surface area in square cm (i.e. pressure) for the respective ribbons. We calculated the average perception threshold of pressure for each ribbon width by dividing the force by the contact area of the ribbon with the arm in square cm, see table III and figure 4.

The data passes Mauchly's test for sphericity (p -value $> .05$) and the Shapiro-wilk test for normality ($p > .05$). Thus, we used a two-way repeated measures ANOVA. We found a significant difference for the ribbon width ($F(2, 20) = 13.43$, $p < .001$), no difference between the left and right arm ($F(1,10) = 1.82$, $p = 0.20$) and no interaction effect ($F(2,20) = 1.3$, $p = 0.29$). We proceeded with a series of paired t-test for the ribbon width. We corrected with the Bonferroni method.

We found significant differences between the 10 mm and 15 mm ribbons ($t(21) = 3.32$, $p < .01$) as well as between the 10 mm and 25 mm ribbons ($t(21) = 4.09$, $p < .01$). We did not find a significant difference between the 15 and 25 mm ribbons ($t(21) = 2.06$, $p = 0.15$).

4) *Comparisons of threshold for reduction of the ribbon between ribbon widths on the left and right arm:* We compared the reduction of the ribbon length between ribbons and, the left and right arm. We calculated the average perception threshold of the ribbon reduction for each ribbon width and arm, see table IV.

The data passes Mauchly's test for sphericity (p -value $> .05$) and the Shapiro-wilk test for normality ($p > .05$). Thus, we used a two-way repeated measures ANOVA. Simple main effect analyses for the arm ($F(1,10) = 0.12$, $p = 0.74$) and ribbon ($F(2,20) = 1.47$, $p = 0.25$) were not significant. The interaction effect was not significant ($F(2,20) = 1.38$, $p = 0.27$).

5) *Comparison between sexes:* We also investigated if there is a difference between sexes. We included the data of the participants who only came for one session (i.e. who completed only the left or right arm, or not all ribbon conditions), see tables V and VI for the descriptive statistics. For those that participated for both a left and right arm session the thresholds were averaged since no difference between left and right arm was found.

The male 15 mm ribbon condition is not normally distributed. Therefore, we used the Wilcoxon rank sum test for this group and an independent t-test for the 10 mm and 25 mm condition. No significant difference between the male and

female participants was found for force for the 10 mm ribbon ($t(6.98) = .45$, p -value $= 0.66$), the 15 mm ribbon ($W = 22$, p -value $= .80$) and the 25 mm ribbon ($t(0.02) = 9.75$, $p = 0.98$).

For pressure only the data of the male 15 mm and 25 mm groups were not normally distributed. We used the Wilcoxon rank sum test for those pair comparisons and a t-test for the 10 mm ribbon comparison. No significant difference between the male and female participants was found for pressure for the 10 mm ribbon ($t(8.66) = .70$, $p = .50$), the 15 mm ribbon ($W = 28$, $p = 1$) and the 25 mm ribbon ($W = 30$, $p = .87$).

For the reduction of ribbon all data were normally distributed. We used independent t-tests. After Bonferroni correction, correcting for 3 tests. We found significant differences between the male and female participants for the 10 mm ribbon ($t(-4.01) = 10.66$, $p < .01$) and the 25 mm ribbon ($t(-3.34) = 12.97$, $p < .05$). No significant difference was found for the 15 mm ribbon ($t(-2.69) = 10.78$, $p = 0.06$).

C. Summary

In experiment 1 we investigated the perception threshold of pressure by textile ribbons of different widths (10 mm, 15 mm, 25 mm). We found no difference for force and ribbon reduction. We did find a difference for pressure. This could be evidence of spatial summation. We did not find a difference between the left and right arm. We did not find a difference between sexes, except for reduction in the 10 mm and 25 mm conditions.

IV. EXPERIMENT 2

Comparing the overall force thresholds of the ribbons in Experiment 1 shows no significant differences between the contact areas of the different sized ribbons. This contrasts with the convincing significant differences found when comparing the pressure thresholds. This suggests that there could be a spatial summation effect, namely when a larger surface area is stimulated, less pressure is needed. Therefore, we explore the possible limit of spatial summation when a force is applied by a textile actuator in Experiment 2. To further explore a possible spatial summation effect, we extended the range of ribbon widths to five levels: 3 mm, 10 mm, 15 mm, 25 mm, and 49 mm.

Compared to Experiment 1, we restricted the experiments to the left arm only, as there were no significant differences between the left and right arm observed in Experiment 1. In addition, we investigated both the upper and lower left arm in two sessions. The upper arm was tested with the set-up placed on a sit/stand desk. The desk was set at the appropriate height for each participant.

We did not find any differences between males and females for force and pressure in Experiment 1. We did find a difference for two ribbon widths (10 mm and 25 mm) for ribbon length reduction. Therefore we repeated that analysis on the lower arm data of Experiment 2.

A. Methods

In this section we describe the research method and procedure, participants and psychophysical method.

The decision to also investigate the upper arm was made later, therefore most participant experienced the lower arm experiment first. Only 4 out of 27 participants with usable data for both the lower and upper arm experienced the upper arm first. However, we do not expect that this order imbalance affected the results in a systematic way.

1) *Participants*: Participants were all aged 18 and above, working or studying at the University of Twente or acquainted with the researchers, 12 male and 17 female in total. Ages from 18 to 59 years (mean = 28.2, median = 25, SD = 10.2). In total, 1 was left-handed and 28 were right-handed. The arm circumference for the lower arm ranged from 18 cm to 27 cm (mean = 22.6, median = 22, SD = 2.14) and from 22.5 cm to 36 cm (mean = 29, median = 28.5, SD = 3.22) for the upper arm. Four participants that participated in Experiment 1, participated in Experiment 2.

2) *Procedure*: The procedure was the same as in Experiment 1. Room temperature was between 20.7 and 24.4 degrees Celsius. The research and Covid-19 procedures were reviewed and approved by the ethics committee of the EEMCS faculty of the University of Twente under number RP 2020-105.

3) *Measures*: The measures are the same as in Experiment 1.

4) *Psychophysical method*: The staircase method used in Experiment 1 turned out to be tedious, having to start far below and above the threshold. This was worsened when a participant made mistakes. Thus, we decided to move forward with a Bayesian method, the PSI method [32] [33]. The PSI method was implemented using the PsychoPy coder [27]. We used a step size of 1, guess rate of 0.5, expected minimum of 0, a stepRange of 70-95, an alphaRange of 0.01-100, a betaRange of 0.01-100, an alphaPrecision of 0.1 and a betaPrecision of 0.1. The step range allowed for trials where no pressure was presented to the participants. The participants were asked the same question as in Experiment 1. We collected priors from the same naive participant for all conditions. This gave a starting point above the lowest step in the range, minimizing participants not feeling the stimulus for several, consecutive trials and therewith minimizing participant insecurity and unnecessary guessing. Participants were presented a stimulus for a total of 35 times per width per location in two sessions (lower and upper arm) of one hour each on two separate days.

B. Results

1) *Data inspection and cleaning*: Of the 29 participants, three were removed because they did not follow the instructions or were consistent outliers (larger than three SD from the mean). Of the 26 remaining participants, three had an incomplete data set due to incomplete data storage and are not included in the paired comparisons.

In this section we make a comparison between the force and pressure data of Experiment 1 and Experiment 2. It is not possible to do this for the data on motor position and reduction as different setting were used in both experiments.

2) *Lower arm*: On the lower arm, we found the perception thresholds for force and pressure, see Table VIII and figures 5 and 6.

3) *Upper arm*: On the upper arm, we found perception thresholds for force and pressure see Table IX and figures 5 and 6.

4) *Average perception threshold reduction in circumference*: We also found the average distance in mm from the start position for the perception threshold, see Table X. Participants were strapped in the set-up at motor step 50. One step corresponds to a total of 1 mm reduction of the ribbon. Namely, one motor step is 0.5 mm, then due to the ribbon being guided past two vertical pulleys the total reduction comes to 1 mm. Shortening the length of the ribbon is related to skin indentation.

5) *Comparing force and pressure for location and ribbon width*: A Shapitro Wilk test ($p < .05$) showed that the data was not normally distributed. The tails of the qq-plot suggested that a log transform could address the problem. The threshold data were transformed with log 10 and then satisfied the assumption of normality and sphericity. Thus, we could go ahead with a repeated measures two-way ANOVA. The analysis only includes participants that returned for both sessions and all ribbon widths and no extreme outliers ($n = 23$).

The two-way ANOVA on ribbon width and arm location revealed two main effects: ribbon width: $F(4, 88) = 7.00$, $p = .003$, and arm location: $F(1, 22) = 27.53$, $p < .001$. The interaction was not significant $F(4, 88) = 0.27$, $p = 0.89$.

As post-hoc on the main effect of ribbon width, a series of pairwise t-test was performed with Bonferroni correction (see Table XI).

A two-way repeated measures ANOVA was conducted that examined the effect of ribbon width and location on arm on perception threshold of force per square cm. There was no interaction effect between of ribbon width and location on arm ($F(4,88) = 0.3$, $p = 0.88$).

Simple main effects analysis of the force per square cm showed that there is a significant difference between ribbon widths ($F(4, 88) = 191.53$, $p < .001$) and no significant difference between the two arm locations ($F(1,22) = 2.49$, $p = 0.13$). We conducted a pairwise test comparing the ribbon widths, see Table XII

6) *Comparing reduction between arm location and ribbon width*: We compared the reduction of the ribbon for all ribbon widths and arm locations. The data does not pass the assumption of normality even after a log transform. Therefore we chose to conduct an aligned ranks ANOVA with the original data. Extreme outliers were removed (larger than three SD from the mean). Simple main effects analysis showed a significant difference for ribbon width ($F(4, 88) = 7.51$, $p < .001$) and location ($F(1, 22) = 48.56$, $p < .001$). There was no significant interaction effect ($F(4,88) = 2.04$, $p = 0.09$).

We followed up with a pairwise comparison between the ribbon widths using the 'art.con' function of the ARTool r package [34] and corrected using the Bonferroni method, see Table XIII. The 'art.con' function conducts contrasts on aligned and ranked linear models.

7) *Comparison force and pressure with Experiment 1:* We compared the thresholds of those that participated in the 10 mm 15 mm and 25 mm conditions for the lower arm to the thresholds found in Experiment 1.

With two two-way mixed measures model ANOVA we examined the total force and pressure for ribbon width and between experiment one and two. After a log 10 transform the data was normal and passed the assumption of sphericity. There was no difference between the two experiments and there was no interaction between ribbon width and experiment for total force and pressure. There is no significant difference between ribbon width for total force. There is a significant difference between ribbon widths for pressure ($F(2, 72) = 30.22, p < .05$).

C. Comparing ribbon reduction between sexes for the lower arm

We compared the reduction of the ribbon around the lower arm at threshold between sexes due to the results of Experiment 1. Since these are two independent groups data of participants who did not complete all sessions or conditions were added.

A shapiro wilk test for each group showed that, the data in the 10 mm ribbon condition for the male group and the 25 mm ribbon for the female group were not normally distributed ($p < .05$) and all other data was normally distributed. For the 10 mm and 25 mm ribbon conditions a Wilcoxon rank sum tests were used, t-tests were used for the 3 mm, 15 mm and 49 mm ribbons.

No significant differences were found for the 3mm ($t(22.72) = 0.61, p = .55$), 10 mm ($W = 65, p = .11$), 15 mm ($t(21.17) = -.44, p = .67$), 25 mm ($W = 84, p = 0.44$) and 49 mm ($t(23.88) = -.21, p = .84$) ribbons.

V. DISCUSSION

A. Spatial summation

We investigated the perception threshold for force and pressure by textile with satin woven ribbons of varying surface areas in two experiments that yielded similar results. The perception threshold for force and reduction of ribbon length (skin indentation) are similar for most surface areas. However, the perception thresholds for N per square cm (i.e. pressure) differs as function of stimulus surface area. Stimuli with a larger surface area require less pressure to be detected. This is a possible indication of spatial summation.

Experiment 1 gave a first indication of spatial summation, we then further investigated this effect in Experiment 2 by employing a larger range of surface areas. The results for this wider range confirm the effect. We also see a plateau in this effect, indicating that the threshold in terms of pressure will not decrease (much) further beyond the largest stimulus used a ribbon width 49 mm. The surface area depends on arm circumference, for example the largest stimulus would be 41.65 cm square for an arm circumference of 20 cm. This spatial summation effect is not in accordance with the common assumption that spatial summation for pressure is small or absent [35]. This assumption is generally accepted, although

TABLE VIII

THE AVERAGE PERCEPTION THRESHOLD TOTAL FORCE AND PRESSURE ON THE LOWER ARM IN NEWTON. THE ABBREVIATION W IN THE LEFT MOST COLUMN REFERS TO RIBBON WIDTH.

W	Total force				Pressure			
	N	Mean	Median	SD	N	Mean	Median	SD
3	29	0.48	0.35	0.45	29	0.15	0.11	0.3
10	29	0.48	0.32	0.42	29	0.04	0.03	0.03
15	29	0.42	0.37	0.22	29	0.03	0.03	0.01
25	29	0.54	0.33	0.42	29	0.02	0.01	0.01
49	29	0.59	0.44	0.42	29	0.01	0.01	0.01

TABLE IX

THE AVERAGE PERCEPTION THRESHOLD TOTAL FORCE AND PRESSURE ON THE UPPER ARM IN NEWTON. THE ABBREVIATION W IN THE LEFT MOST COLUMN REFERS TO RIBBON WIDTH.

W	Total force				Pressure			
	N	Mean	Median	SD	N	Mean	Median	SD
3	25	1.05	0.67	0.88	25	0.2	0.14	0.15
10	24	0.59	0.32	0.73	24	0.05	0.04	0.04
15	26	1.08	0.72	1.02	26	0.04	0.03	0.04
25	26	1.29	1.03	1.17	26	0.03	0.03	0.03
49	26	1.34	0.829	1.6	26	0.016	0.01	0.02

TABLE X

THE AVERAGE POSITION FROM THE START IN MM. THE ABBREVIATION W IN THE LEFT MOST COLUMN REFERS TO RIBBON WIDTH.

W	Lower arm				Upper arm			
	N	Mean	Median	SD	N	Mean	Median	SD
3	30	27.6	27.3	3.35	26	31.5	32.1	4.27
10	30	28.7	27.1	6.81	25	29.2	29.2	3.62
15	30	27.6	27.9	3.47	27	30.7	30.7	4.36
25	30	27.7	26.6	3.55	27	31.1	30.4	4.18
49	30	28.7	28.5	3.52	27	34.3	34.1	4.18

TABLE XI

RESULTS OF THE POST-HOC TEST ON THE MAIN EFFECT OF RIBBON WIDTH ON THE THRESHOLD IN ABSOLUTE FORCE.

	3	10	15	25	49
3	-	1	1	.08	< .01
10	-	-	1	.31	< .001
15	-	-	-	.24	< .001
25	-	-	-	-	1

TABLE XII

RESULTS OF THE POST-HOC TEST ON THE MAIN EFFECT OF RIBBON WIDTH ON THE THRESHOLD IN PRESSURE.

	3	10	15	25	49
3	-	< .001	< .001	< .001	< .001
10	-	-	< .001	< .001	< .001
15	-	-	-	.01	< .001
25	-	-	-	-	< .001

TABLE XIII

PAIRWISE COMPARISON OF RIBBON REDUCTION BETWEEN ALL RIBBON WIDTHS.

	3	10	15	25	49
3	-	1	1	1	0.02
10	-	-	1	1	< .001
15	-	-	-	1	< .001
25	-	-	-	-	< .01

there is little information supporting this assumption. From the perspective of ecological validity, spatial summation of force makes sense as it for instance allows estimating the mass of an object irrespective of the momentaneous contact area.

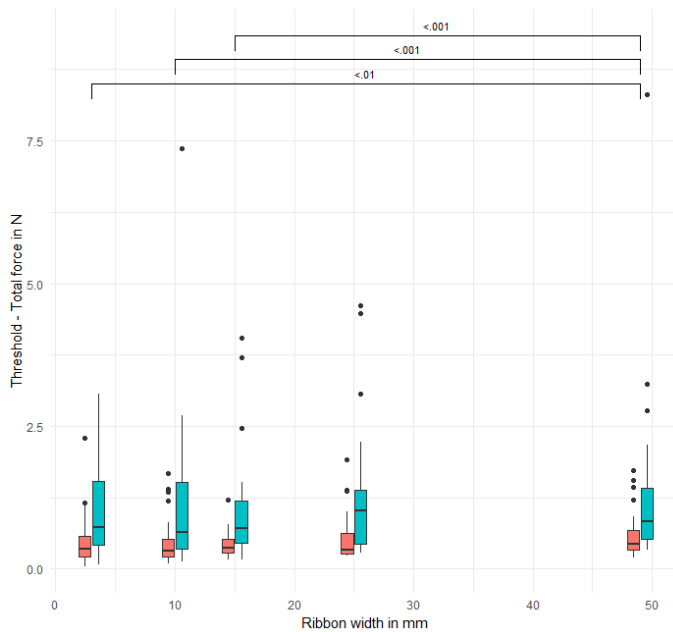


Fig. 5. The distribution of the absolute force thresholds found for different ribbon widths on the lower and upper arm. The dots indicate individual participants, the colours the lower and upper arm, the lines above the boxplots are accompanied by significant p-values found when comparing the conditions. The box plots follow standard Tukey representations.

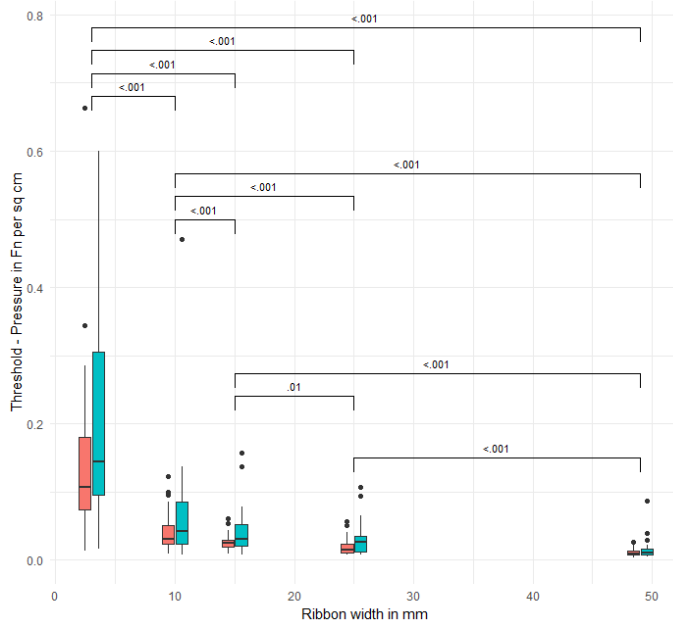


Fig. 6. The distribution of the pressure thresholds found for different ribbon widths on the lower and upper arm. The dots indicate individual participants, the colours the upper and lower arm, the lines above the boxplots are accompanied by significant p-values found when comparing the conditions. The box plots follow standard Tukey representations.

Object mass is a much more ecological relevant object feature than pressure. It also means that the estimation of object mass remains constant if the contact area changes.

The literature regarding (spatial) integration or summation of tactile stimuli mostly concerns vibration stimuli [35]–[37], and nociception of pressure and of temperature [38], [39]. We will look into the assumed underlying mechanisms for spatial

summation for these stimuli to see if and to what extent they may be applicable for pressure stimuli.

1) *Pressure pain*: [39] found a spatial summation effect for pressure pain when looking at stimuli of 0.5, 1 and 2 square centimetres. This was tested on varying body regions (the dorsal area of the hand, and two sites on the upper back) and results were similar across the different testing sites. They also found that size of the surface area influenced the quality of the experienced pain. Small areas felt like a prick versus a pressure pain for large areas. [38] also found spatial summation when presenting participants with a pressure pain stimulus. They explored bigger areas up to 8 square centimetres. [40] also investigated spatial summation in pressure pain. For their study they opted to split pain, pressure and sharpness to find thresholds and explore spatial summation effects for all three concepts. Probes at a size of 0.05 mm and 0.1 mm were used. They found spatial summation for both pressure and pain separately, with pressure showing a greater spatial summation effect.

2) *Pressure*: Considering that spatial summation occurs on the P channel [35], [36], [41], it is conceivable that it could also happen on other channels. We hypothesize that spatial summation can occur in mechanoreceptor channels other than the P-channel, something suggested previously by [37] and supported by the research efforts into pressure pain as listed above and supported by [42] who investigated Just Notable Difference (JND) pressure thresholds in relation to surface area and found that a larger surface results in a smaller JND.

Holway and Crozier [42] also investigated the effect of perimeter (edges) on the JND of pressure and found no significant effect. We do not know if this is also the case in our experiment. In our case, both the moving ribbon and the static ribbon have edges, the additional edges could potentially have an effect on the measured thresholds. However, the edges of the various ribbons are the same length, so a potential effect would be the same across conditions.

a) *Function of pressure spatial summation* : Figures 5 and 6 indicate a linear function when looking at the averages of the total force perception thresholds. The averages of the force per square cm thresholds in Figures ?? and ?? indicate a decaying exponential function. The larger the width of the ribbon and thus the surface area, the lower the force per square cm required to detect the stimulus. The curve seems to reach its asymptote at a ribbon width of 25 mm. This suggests that there is a minimum force per square cm necessary to perceive a pressure touch of any surface area. If no spatial summation occurs, we would expect to see two similar functions for both the total force and force per square cm.

b) *Indentation*: Indentation is a factor in perception of tactile cues [43] and could play a part in the spatial summation of the pressure we investigated. It takes a certain force to deform the skin and indent the mechanoreceptors. The force and indentation needed to perceive a stimulus may change based on the properties of the skin and mechanoreceptors.

The receptor potential that follows from activation of mechanotransducer channels is an input signal for the primary sensory neuron. It is transformed into a neural pulse code where frequency of action potentials reflects the intensity of

the stimulus. After prolonged stimulation, the frequency of the action potentials diminishes [44].

We found that the reduction of the ribbon around the arm at threshold is similar for most ribbon widths, except when comparing the smallest 3 mm ribbon to the widest ribbon of 49 mm. These results are similar to the results found for total force.

With just that information it is hard to say what the exact roles of force and indentation are for our stimulus. In a future study we need to further explore the relationship between indentation and force when it comes to perception of pressure on the forearm. To investigate if indentation per square cm lowers the perception threshold like force we can measure deformation by developing a camera set-up that can be used with the current experimental set-up.

c) *Contact area form and orientation:* The motorized ribbon presents pressure across the width of the arm. We did not test the same surface area across the length of the arm. If there is symmetry in spatial integration between the width of the arm and the length of the arm, we would expect to find the same results when applying pressure with a contact of the same size in both directions. Of the mechanoreceptors capable of sensing pressure, Ruffini endings have the largest receptive field, 59 mm square on average. The size and shape of the receptive field could potentially influence spatial integration of pressure stimuli. However, this is likely more relevant for stimuli with surface areas in the same order as the receptive field size. The surface areas we employed in our experiments are about an order of magnitude larger indicating summation over multiple receptive fields. This makes it unlikely that the shape and size of the receptive fields plays an important role. Another question is whether edges influence spatial integration. All ribbons in our experiment are of the same length and in one piece, thus they have the same edges along the length of the ribbon, irrespective of their surface area. For an arm circumference of 20 cm, the estimated length of these edges is 85 mm. However, the edges along the width of the ribbon vary with the width, i.e. from 3 to 49 mm. [42] investigated the JND for a full surface, the edge and the centre of the same circle and found no difference between the edge and the centre. This suggests that surface area is the main factor for pressure thresholds and edges do not play a (major) role. However, further research could provide more insight.

3) *Vibration:* [35], [36] state that spatial summation happens in the P-channel. [41] found a spatial summation effect in the P-channel at vibration of 250Hz and found that smaller contact areas that have a higher gradient and curvature of displacement have higher thresholds on the glabrous skin. [35] offers two factors' combined effects as an explanation: probability summation and neural integration. Probability summation is explained as follows: the neural thresholds of P-channel receptors cover a wide range of intensities and are present in an optimal density for the probability of stimulation to increase as the size of the contactor is increased. An actuator covering a bigger surface area of the skin increases the probability that the most sensitive receptors are activated. Neural integration refers to the summation of neural activity over the activated receptors. The authors state that the exact location where in

the system this occurs is unknown. According to [35] both processes play a role in spatial summation and each require an optimal receptor density. This leads to the hypothesis that receptor density is a major factor in spatial summation. Followed by a second hypothesis that "the P-channel is the only channel that possesses a neural-integration mechanism capable of summing the neural activity that originates in individual receptors." In our investigation, we found a spatial summation effect of pressure stimuli, suggesting that the P-channel is not the only channel capable of spatial integration and contradicting the second hypothesis by [35]. More relevant, however, is the first hypothesis stated by [35], namely that spatial integration occurs with optimal receptor density (in the P-channel). We hypothesize that the same mechanism also occurs in the NP II channel (linked to Ruffini endings) given that the same requirements are met as discussed for the P-channel. Although the lack of spatial summation has been shown for the NP I and NP III channels, this is not explicitly investigated for the NP II channel. Receptor density varies per location, this is also true for pressure sensitive mechanoreceptors.

Free nerve endings in the hairy skin are common, and some are sensitive to light touch [45]. It likely that these nerve endings are excited by our pressure stimulus and thus could play a role in the spatial summation we found.

B. Comparing body locations and sex

Experiment 1 showed that there are no differences in perception threshold for the left and right arm. Experiment 2 showed that the thresholds on the lower arm are lower than on the upper arm for force, but no significant difference was found for pressure. The difference in circumference of the lower and upper arm is a possible explanation for the larger threshold for force and the same thresholds for pressure. The average arm circumferences of our participants are 22.6 cm for the lower and 28.5 cm for the upper arm. A bigger circumference means a larger area of contact with the ribbon wrapped around the arm. To apply the same pressure to a larger area, a greater force is required.

For certain tactile sensitivities sex differences are found, for example, [19] females have lower thresholds for two-point discrimination. Therefore we explored whether this was the case for our pressure stimulus. We did not find a difference between male and female participants for force or pressure. We did find a difference for reduction of ribbon length for two conditions (10 mm and 25 mm) in Experiment 1. Reduction of ribbon length is an indirect measure of skin indentation. It could be that indentation needed to perceive a stimulus is different for males and females as both sexes have a different muscle to fat ratio and skin thickness [18]. It is possible that there were other disrupting variables at play during Experiment 1 since we could not replicate the results in Experiment 2 where we investigated a greater variation of contact area size and had a larger number of participants.

C. Limitations

We investigated only the pressure stimulus of textile on the skin. When a piece of clothing contracts around the arm, it

would make sense that it also moves or twists and creates shear forces on the arm. This activates the mechanoreceptors around the hair follicles. We chose to separate the two types of forces as to not confuse the participants and to clearly measure only one of the two. It is possible that our setup with an arm-fixed layer in between the contracting ribbon and the observer's skin, could have spread the forces around the edges of the top ribbon. This would have reduced the possible effect of edges as discussed in Section V-A above.

VI. CONCLUSION

To conclude, (1) We found evidence of spatial integration. Where a bigger ribbon covering a bigger surface area needs to exert less force per square cm to be perceived than a smaller ribbon. This is an advantage as the force produced by electroactive textile increases when multiple yarns are woven together linearly [3], (2) There seem to be some limits to the spatial integration we found. With each increase of ribbon width the difference with the previous becomes smaller, where the relationship between surface area and pressure follows an asymptote.

These findings can guide the design of a wearable with textile, haptic actuators and design of other haptic actuators that present a pressure stimulus. When we design these actuators a minimal pressure force has to be applied to create a perceivable stimulus, this value is larger if the covered surface is smaller.

VII. ACKNOWLEDGEMENTS

We want to thank Federigo Califano, Edwin Jager and Carin Backe.

REFERENCES

- [1] B. McGrath, A. McKinley, M. Duistermaat, O. Carlander, C. Brill, G. Zets, and J. Van Erp, "Tactile actuator technology," *Tactile Displays for orientation, navigation and communication in air, sea and land environments*, p. 4, 2008.
- [2] C. Backe, L. Guo, E. Jager, and N.-K. Persson, "Towards responding fabrics: textile processing of thin threadlike pneumatic actuators," in *5th Ed. Smart Materials and Surfaces-SMS Conference, Lisbon, 23-25 October 2019*, 2019.
- [3] A. Maziz, A. Concas, A. Khaldi, J. Stålhand, N.-K. Persson, and E. W. Jager, "Knitting and weaving artificial muscles," *Science advances*, vol. 3, no. 1, p. e1600327, 2017.
- [4] D. Mellling, J. G. Martinez, and E. W. Jager, "Conjugated polymer actuators and devices: Progress and opportunities," *Advanced Materials*, p. 1808210, 2019.
- [5] T. E. of Encyclopaedia Britannica, "Pressure," Sep 2022. [Online]. Available: <https://www.britannica.com/science/pressure>
- [6] S. J. Lederman and R. L. Klatzky, "Hand movements: A window into haptic object recognition," *Cognitive psychology*, vol. 19, no. 3, pp. 342–368, 1987.
- [7] R. S. Johansson and G. Westling, "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects," *Experimental brain research*, vol. 56, no. 3, pp. 550–564, 1984.
- [8] C. M. Nunez, "Design and perception of wearable multi-contact haptic devices for social communication," Ph.D. dissertation, Stanford University, 2021.
- [9] B. Benoit, K. Boerner, M. Campbell-Yeo, and C. Chambers, "The power of human touch for babies," *Canadian Association of Pediatric Health Center. Retrieved on September*, vol. 26, 2018.
- [10] J. B. Butts, "Outcomes of comfort touch in institutionalized elderly female residents," *Geriatric Nursing*, vol. 22, no. 4, pp. 180–184, 2001.
- [11] J. T. Suvilehto, E. Glerean, R. I. Dunbar, R. Hari, and L. Nummenmaa, "Topography of social touching depends on emotional bonds between humans," *Proceedings of the National Academy of Sciences*, vol. 112, no. 45, pp. 13 811–13 816, 2015.
- [12] "Feelhey – hey." [Online]. Available: <https://feelhey.com/>
- [13] G. Huisman, "Social touch technology: A survey of haptic technology for social touch," *IEEE transactions on haptics*, vol. 10, no. 3, pp. 391–408, 2017, not fully read yet.
- [14] A. D. Cheok, "Huggy pajama: A remote interactive touch and hugging system," in *Art and technology of entertainment computing and communication*. Springer, 2010, pp. 161–194.
- [15] R. Wang, F. Quek, D. Tatar, K. S. Teh, and A. Cheok, "Keep in touch: channel, expectation and experience," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2012, pp. 139–148.
- [16] W. Wu and H. Culbertson, "Wearable haptic pneumatic device for creating the illusion of lateral motion on the arm," in *2019 IEEE World Haptics Conference (WHC)*. IEEE, 2019, pp. 193–198.
- [17] B. Jumet, Z. A. Zook, A. Yousaf, A. Rajappan, D. Xu, T. F. Yap, N. Fino, Z. Liu, M. K. O'Malley, and D. J. Preston, "Fluidically programmed wearable haptic textiles," *Device*, vol. 1, no. 3, 2023.
- [18] P. U. Giacomoni, T. Mammone, and M. Teri, "Gender-linked differences in human skin," *Journal of dermatological science*, vol. 55, no. 3, pp. 144–149, 2009.
- [19] D. B. Boles and S. M. Givens, "Laterality and sex differences in tactile detection and two-point thresholds modified by body surface area and body fat ratio," *Somatosensory & motor research*, vol. 28, no. 3-4, pp. 102–109, 2011.
- [20] A. W. Goodwin and H. E. Wheat, "Physiological mechanisms of the receptor system," in *Human haptic perception: basics and applications*. Springer, 2008, pp. 93–102.
- [21] S. J. Lederman and R. L. Klatzky, "Haptic perception: A tutorial," *Attention, Perception, & Psychophysics*, vol. 71, no. 7, pp. 1439–1459, 2009.
- [22] A. Vallbo, H. Olsson, J. Wessberg, and N. Kakuda, "Receptive field characteristics of tactile units with myelinated afferents in hairy skin of human subjects," *The Journal of physiology*, vol. 483, no. 3, pp. 783–795, 1995.
- [23] Å. Vallbo, H. Olsson, and J. Wessberg, "Unmyelinated afferents constitute a second system coding tactile stimuli of the human hairy skin," *Journal of neurophysiology*, vol. 81, no. 6, pp. 2753–2763, 1999.
- [24] L. S. Löken, J. Wessberg, F. McGlone, and H. Olsson, "Coding of pleasant touch by unmyelinated afferents in humans," *Nature neuroscience*, vol. 12, no. 5, pp. 547–548, 2009.
- [25] R. Ackerley, K. Saar, F. McGlone, and H. Backlund Wasling, "Quantifying the sensory and emotional perception of touch: differences between glabrous and hairy skin," *Frontiers in behavioral neuroscience*, vol. 8, p. 34, 2014.
- [26] C. Reas and B. Fry, "Processing: programming for the media arts," *Ai & Society*, vol. 20, no. 4, pp. 526–538, 2006.
- [27] J. Peirce, J. R. Gray, S. Simpson, M. MacAskill, R. Höchenberger, H. Sogo, E. Kastman, and J. K. Lindelöv, "Psychopy2: Experiments in behavior made easy," *Behavior research methods*, vol. 51, no. 1, pp. 195–203, 2019.
- [28] J. Weda, J. van Erp, and A. Mader, "The effect of actuation speed on the perception threshold of a squeezing soft actuator," *IEEE Transactions on Haptics*, 2023.
- [29] N. Prins et al., *Psychophysics: a practical introduction*. Academic Press, 2016, an introduction to psychophysical methods. gives a good categorization of methods and when to use what method and analysis.
- [30] M. R. Leek, "Adaptive procedures in psychophysical research," *Perception & psychophysics*, vol. 63, no. 8, pp. 1279–1292, 2001.
- [31] D. Linares and J. López-Moliner, "quickpsy: An R package to fit psychometric functions for multiple groups," *The R Journal*, vol. 8, no. 1, pp. 122–131, 2016. [Online]. Available: <https://journal.r-project.org/archive/2016-1/linares-na.pdf>
- [32] N. Prins, "The psi-marginal adaptive method: How to give nuisance parameters the attention they deserve (no more, no less)," *Journal of vision*, vol. 13, no. 7, pp. 3–3, 2013.
- [33] L. L. Kontsevich and C. W. Tyler, "Bayesian adaptive estimation of psychometric slope and threshold," *Vision research*, vol. 39, no. 16, pp. 2729–2737, 1999.
- [34] M. Kay, L. A. Elkin, J. J. Higgins, and J. O. Wobbrock, *ARTool: Aligned Rank Transform for Nonparametric Factorial ANOVAs*, 2021, R package version 0.11.1. [Online]. Available: <https://github.com/mjskay/ARTool>

- [35] G. Gescheider, J. Wright, and R. Verrillo, "Information-processing channels in the tactile sensory system: A psychophysical and physiological analysis new york," 2009.
- [36] G. A. Gescheider, B. Güçlü, J. L. Sexton, S. Karalunas, and A. Fontana, "Spatial summation in the tactile sensory system: Probability summation and neural integration," *Somatosensory & motor research*, vol. 22, no. 4, pp. 255–268, 2005.
- [37] H. Muijser, "An indication for spatial integration in a non-pacinian mechanoreceptor system?" *The Journal of the Acoustical Society of America*, vol. 96, no. 2, pp. 781–785, 1994.
- [38] H. Nie, T. Graven-Nielsen, and L. Arendt-Nielsen, "Spatial and temporal summation of pain evoked by mechanical pressure stimulation," *European journal of pain*, vol. 13, no. 6, pp. 592–599, 2009.
- [39] R. Defrin, A. Ronat, A. Ravid, and C. Peretz, "Spatial summation of pressure pain: effect of body region," *Pain*, vol. 106, no. 3, pp. 471–480, 2003.
- [40] J. GREENSPAN1, M. Thomadaki, and S. McGILLIS, "Spatial summation of perceived pressure, sharpness and mechanically evoked cutaneous pain," *Somatosensory & motor research*, vol. 14, no. 2, pp. 107–112, 1997.
- [41] R. T. Verrillo, "Effect of contactor area on the vibrotactile threshold," *The Journal of the Acoustical Society of America*, vol. 35, no. 12, pp. 1962–1966, 1963.
- [42] A. H. Holway and W. J. Crozier, "The significance of area for differential sensitivity in somesthetic pressure," *The Psychological Record*, vol. 1, p. 177, 1937.
- [43] K. O. Johnson, "The roles and functions of cutaneous mechanoreceptors," *Current opinion in neurobiology*, vol. 11, no. 4, pp. 455–461, 2001.
- [44] J. Hao, C. Bonnet, M. Amsalem, J. Ruel, and P. Delmas, "Transduction and encoding sensory information by skin mechanoreceptors," *Pflügers Archiv-European Journal of Physiology*, vol. 467, pp. 109–119, 2015.
- [45] K. S. Park, "Sensory receptors," in *Humans and Electricity: Understanding Body Electricity and Applications*. Springer, 2023, pp. 123–145.

Jan van Erp Jan van Erp is interested in human-computer interaction, human perception, haptics, brain-computer interfaces, robotics; he is a Full Professor in the Human Media Interaction department of the University of Twente and in the Netherlands Organization for Applied Scientific Research (TNO).

Judith Weda Judith Weda has an interest in human-computer interaction, wearable technology, haptics, mediated social touch and human expression through technology; she has a B.Sc in Creative technology, a M.Sc in Human Media Interaction and is currently a PhD student in the Human Media Interaction group of the University of Twente.

Angelika Mader Angelika Mader is an associate professor in the Human Media Interaction group of the University of Twente. Her research interests include human-computer interaction, wearable technology and haptics; she is involved in the Creative Technology bachelor and Interaction technology master programmes.

Hamid Souri Hamid Souri received his B.Sc. degree in mechanical engineering from Sharif University of Technology, Iran, in 2012, and his M.Sc. degree in civil and environmental engineering from KAIST, South Korea, in 2015. He obtained his Ph.D. in mechanical engineering at the University of Auckland, New Zealand, in 2019. His research interests include flexible electronic devices for healthcare, smart materials, and composite materials.

Edwin Dertien Edwin Dertien (MSc, PhD) works as Assistant Professor in the Robotics and Mechatronic group at the University of Twente and teaches in the Creative Technology and Interaction technology programmes. His research focuses on robotics for inspection, maintenance, care and cure, using soft robotics, haptics, HRI, theatre and tinkering.