This article has been accepted for publication in IEEE Transactions on Haptics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TOH.2023.3273774

The Effect of Actuation Speed on the Perception Threshold of a Squeezing Soft Actuator

Judith Weda, Jan van Erp and Angelika Mader

***Abstract*—The actuation speed of a pressure stimulus may influence its perception threshold. This is relevant for the design of haptic actuators and haptic interaction. We ran a study using a motorized ribbon to apply pressure stimuli (squeezes) to the arm at three different actuation speeds and used the PSI method to find the perception threshold for 21 participants. We found a significant effect of actuation speed on the perception threshold. Namely, a lower speed seems to increase the thresholds of normal force, pressure and indentation. This could be due to multiple factors like temporal summation, stimulating a larger population of mechanoreceptors for faster stimuli, and different responses of SA and RA receptors to stimuli of varying speeds. Our results show that actuation speed is an important parameter for the design of new haptic actuators and the design of haptic interaction for pressure.**

***Index Terms*—Pressure, Squeezing, Soft actuator, Psychophysics, Perception threshold, Application speed.**

I. Introduction

In haptic and tactile interaction, it is important that a stimulus is perceivable and of predictable perceived magnitude. Perception of a stimulus may depend on the contact area, frequency, amplitude, and other stimulus parameters. During our previous work on haptic actuators that provide a pressure stimulus around the arm (i.e. squeezing) we observed that some participants did not feel a stimulus with a low actuation speed while they felt a stimulus of the same force and surface area presented at a higher actuation speed. These observations led us to hypothesize that actuation speed influences the perception threshold of pressure stimuli.

There is an increasing interest in the development of haptic bracelets that deliver squeeze-like pressure for warnings and social touch on the arm [1]–[4]. The arm is a location that is accepted for social touch by many different relationships [5]. The hairy skin on the dorsal side of the arm is a logical place for receiving direct social touch, and thus of interest for mediated social touch. Despite the increasing interest there is little known about for instance the pressure threshold on the arm and effects of parameters like speed of contraction, or the reported results are contradictory.

The effect of actuation speed on perception is relevant in order to design effective haptic interaction for varying actuators such as pneumatic [2], [3], memory coil [4], fluid based [6], [7] and electroactive textile [8] solutions.

As far as the authors are aware, there is a gap in the literature on the effect of speed on the perception threshold of pressure stimuli on the arm. Therefore, we additionally discuss adjacent work investigating the effect of speed on suprathreshold indentation and skin stretch stimuli. The investigated effects are on mechanoreceptor response and magnitude perception.

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

A. Mechanoreceptors

The characteristics of the mechanoreceptors in the human glabrous skin have been investigated more in depth than the mechanoreceptors in the human hairy skin. It has been found that the glabrous skin of the hands (90 afferent units/cm^2) is more densely innervated than the hairy skin of the arm (13 afferent units/cm^2) [9]. The following types of mechanoreceptors have been found in both types of skin: Merkel cells, Ruffini corpuscles and Pacinian corpuscles. Meissner's corpuscles are typical for the glabrous skin. In the hairy skin hair units, field units can be found. Mechanoreceptors are categorized as slowly adapting (SA) like the Ruffini corpuscles and the Merkel cell, or rapidly adapting (RA) like the hair units, field units, Meissner corpuscles and Pacinian corpuscles tactile receptors. Mechanoreceptors respond to different types of touch: Pacinian corpuscles are most sensitive to vibration, Meissner corpuscles to dynamic skin indentation, Merkel cells to sustained indentation and Ruffini corpuscles to skin stretch [9], [10]. Often, multiple populations of varying types of mechanoreceptors respond to a single, natural touch [11].

In [12] the authors investigated the firing rate of different channels in the human radial nerve in the back of the hand and forearm when the skin was stretched at different velocities. They found that SA afferents fired consistently across velocities. They also found that RA afferents did respond to higher velocities, but did not respond or responded poorly to the lower velocities. In [13] the authors found that in the glabrous skin of the macaque monkey the receptive field (RF) size for RA afferents was mostly dependent on the actuation speed of an indentation stimulus. They found that for SAI (Merkel cell) the RF size was mostly dependent on load (force) and that with increasing speed and forces the RF for both RA and SA increases. In addition, they found that at very slow application rates the RA response was so minimal that the total found response can be considered to be completely from SAI afferents.

B. Effect of actuation speed on perception of haptic pressure stimuli

The work presented in [13] was in combination with a study on the human perception of the same stimuli [14]. The authors found that actuation speed (1, 10, and 100 g/s) influenced the perceived magnitude of pressure sensations.

The results of the work in [14] seem to contradict the results found in [15]. There the authors tested different rate of force changes (0.10 N/s (10 g/s), 0.15 N/s (15 g/s) and 0.30 N/s (30 g/s)) for both tangential and normal forces on the human fingertip. They found that the rate of force change did not influence the magnitude perception of the applied forces.

This article has been accepted for publication in IEEE Transactions on Haptics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TOH.2023.3273774

Actuation speed has an effect on perceived magnitude of skin stretch stimuli. Faster stimuli are perceived as stimuli of a larger magnitude than slower stimuli [16], [17].

This leads us to the following research question:

”To what degree does actuation speed influence the perception threshold for pressure stimuli by a textile actuator on the dorsal side of the lower arm?”

II. Method

A. Apparatus

The motorized ribbon is depicted in Figure 1. Participants placed their arm (left) on top of a bench (A) and adjustable supports (B). A ribbon (C, satin woven polyester, 15 mm) was guided past bearings (D) in the bench and around the arm (E) and attached to a motor (F, L12 series by Actuonix, with a stroke of 50 mm and 1:100 gear ratio, 13 mm/s speed and peak power of 23 N). The motor then pulled on the ribbon and the force on the ribbon was measured by two load cells (G, (strain gauge based, CZL-635, 0-5 kg) on each end. To avoid shear and friction forces and skin stretch, an arm-fixed 78 mm wide ribbon (H, satin woven polyester) served as layer in between the skin and the motorized ribbon. Participants indicated whether they felt the ribbon on their arm when prompted by a question displayed on the screen in front of them (I). Direct view of their left arm was blocked by a divider (J). See [2] for more information about the set-up. A Psychopy script communicated with the motorized ribbon setup via an Arduino script [18]. The sketch increased or decreased the length of the ribbon by 0.5 mm for one discrete motor step. One motor step (unloaded) took 38.5 ms to complete. The time in between the onset of two consecutive motor steps determined the final actuation speed. This time was varied in three contraction speed conditions: 38.5 ms, equivalent to 13.00 mm/s actuation speed, 38.5 ms + 120 ms delay, equivalent to 4.17 mm/s, and 38.5 ms + 240 ms delay, equivalent to 2.08 mm/s. The decision for the delays was made after a pilot test.

B. Calculation of normal force

We used equations based on the capstan principle to calculate the normal force (Fn). 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 equation 1, where Tl and Tr refers to the tension on the left and right of the ribbon as measured by the left and right load cell respectively, and delta theta is the length of the contact area of the ribbon on the arm in radians:

$$Fn = (Tl + Tr) \times d\theta/2 \quad (1)$$

We assumed that there is negligible friction due to the use of a smooth layer between the arm and the ribbon, and that the arm is a perfect cylinder. We found that in the current set-up, $\delta\theta$ is different for each arm circumference. Therefore, we 3D-printed cylinders of different circumferences and placed them in the set-up to find the length of the contact area in degrees by marking where the ribbon touches the cylinder and then

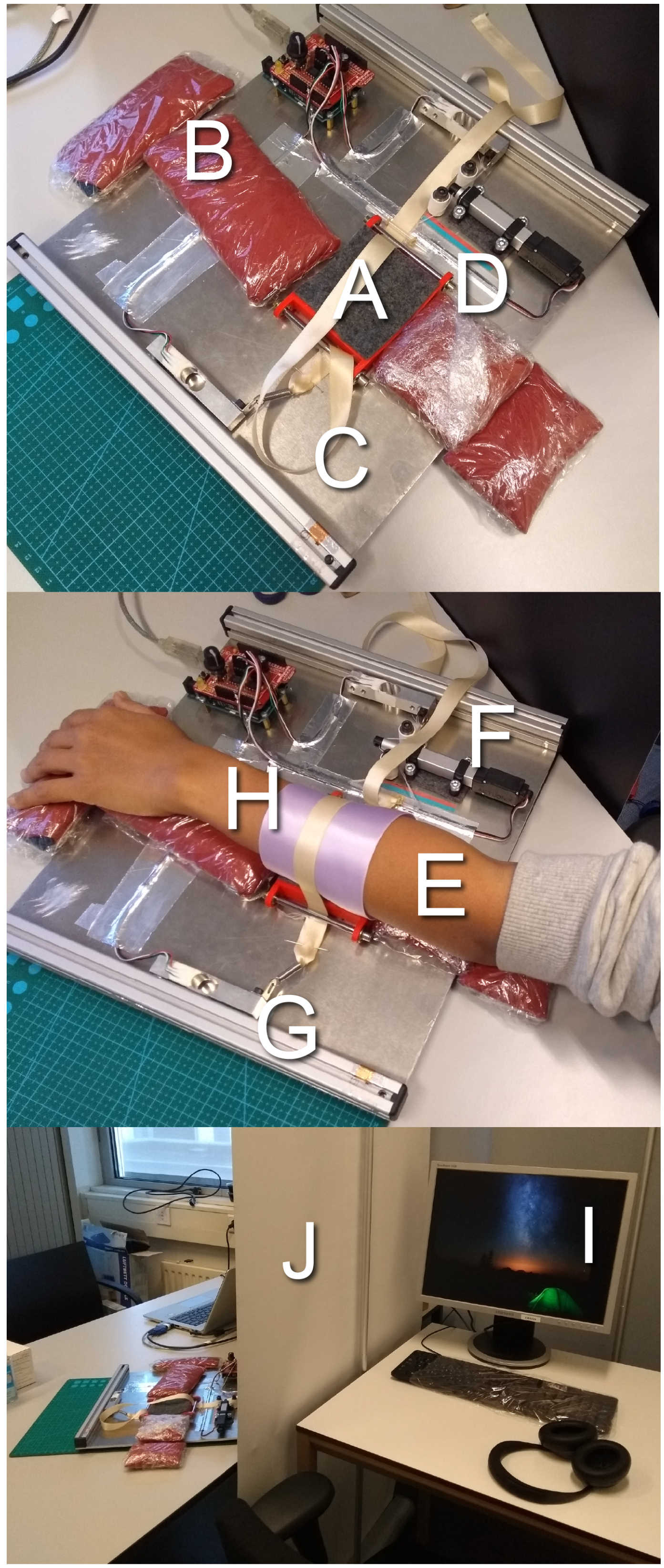

Figure 1: Motorized ribbon set-up and participant with arm in the set-up. A: Bench, B: Support, C: Motorized ribbon, D: Bearing, E: Lower arm (left), F: Motor, G: Load cell, H: Separating ribbon, I: Monitor, J: Divider.

This article has been accepted for publication in IEEE Transactions on Haptics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TOH.2023.3273774

measured the degrees with a protractor. The measured 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: The length of the contact area (CA) of the ribbon on the arm in degrees per arm circumference found by placing 3D-printed cylinders of different sizes in the set-up.

Circumference in cm	Length of CA in degrees	Length of CA 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 pressure or the force per square cm we divided the normal force (Fn) by the total arm surface touched by the ribbon, which is the ribbon width (1.5 cm) multiplied by the length of the contact area in cm.

C. *Participants*

Twenty-one volunteers participated. After data inspection, we removed two participants from the analysis due to incomplete sessions and two because their performance was three SD from the mean. Of the 17 participants remaining in the dataset, 9 were female, and 1 was left-handed. Ages ranged from 21 to 48, with an average age of 28.9 (M = 27, SD = 7.57). Participants had an arm circumference from 19 to 28 cm, with an average of 23.2 (M = 23, SD = 2.63). Participants were students and employees of the University of Twente. Students received a €5 giftcard for their participation. The study was approved by the EEMCS ethics committee of the University of Twente under reference 2022-19.

D. *Psychophysical method*

We used the PSI method [19] [20] as written in the Psychopy library [21]. The PSI method is a Bayesian method. The algorithm chooses the next stimulus that should be presented based on the participant's previous answers, gathered priors and the experiment parameters. This allows for a relatively quick approximation of thresholds. Priors were collected beforehand. Our settings in Psychopy were: step size: 1; motor step range: 70-95; trials: 36; alphaRange: [0.01,100]; betaRange: [0.01,100]; alphaPrecision: 0.1; betaPrecision: 0.1; delta: 0.5; expected minimum: 0.

The step size is the smallest step size possible for changing the motor position while also accurately reading the motor position with the Arduino 'servo.read()' function. The motor step range was found after a pilot as range in which we can find the perception threshold for all participants. The number of trial is the largest number of trials while still completing all three condition in an amount of time (one hour) that does not ask too much from the participants. In addition, it is sufficient to find the perception threshold. AlphaRange, betaRange, alphaPrecision and betaPrecision were determined through piloting. Delta is one divided by the number of response options per trial. The expected minimum value is zero.

E. *Analytic strategy*

The collected data was analyzed in R using the quickpsy package [22] among others. S-curves were fitted to find the threshold at .75. We calculated the descriptive statistics and performed a six repeated measures ANOVAs with actuation speed (2.08 mm/s, 4.17 mm/s, and 13.00 mm/s) as independent variable for the following three dependent variables: threshold of normal force, threshold and slope of pressure (force per square cm), threshold of motor position (equivalent to reduction in circumference of the ribbon). When a dependent variable violated the assumption of sphericity, we report the Greenhouse-Geiser corrected p value marked as pcorrected. Significant main effects were further analyzed with post-hoc pair-wise comparisons adjusted for multiple testing by the Bonferroni method. When a dependent variable violated the assumption of normality, we used the Friedman test and further analyzed with Connover tests for post-hoc pairwise comparison.

F. *Procedure*

Participants were welcomed and given written information about the experiment. After agreeing to participate, they signed the informed consent form. Their left lower arm was measured lengthwise (from the elbow to the wrist) to find and mark the middle. Their arm circumference was measured at this middle point and a broad ribbon (78 mm, marked H in Figure 1) was placed around their arm to prevent rubbing the hair and shear forces. The researcher explained that the motorized ribbon (marked C in Figure 1) would contract and that they would feel the ribbon pressing on their arm or not. When prompted they would answer yes or no. The arm of the participant was placed in the set-up, and they received a single, ample above threshold stimulus to familiarize themselves with the "squeezing sensation". After this data collection started. The order of the three contraction speed conditions was randomized. Afterwards, participants were debriefed and students received their gift card. Guidelines for COVID-19 prevention were followed during the experiment.

III. Results

A. *Fit*

For each participant, we fitted the proportion yes answers to an s-curve using the logistic function for the normal force, see Figure 2a, the pressure, see Figure 2b and the motor position

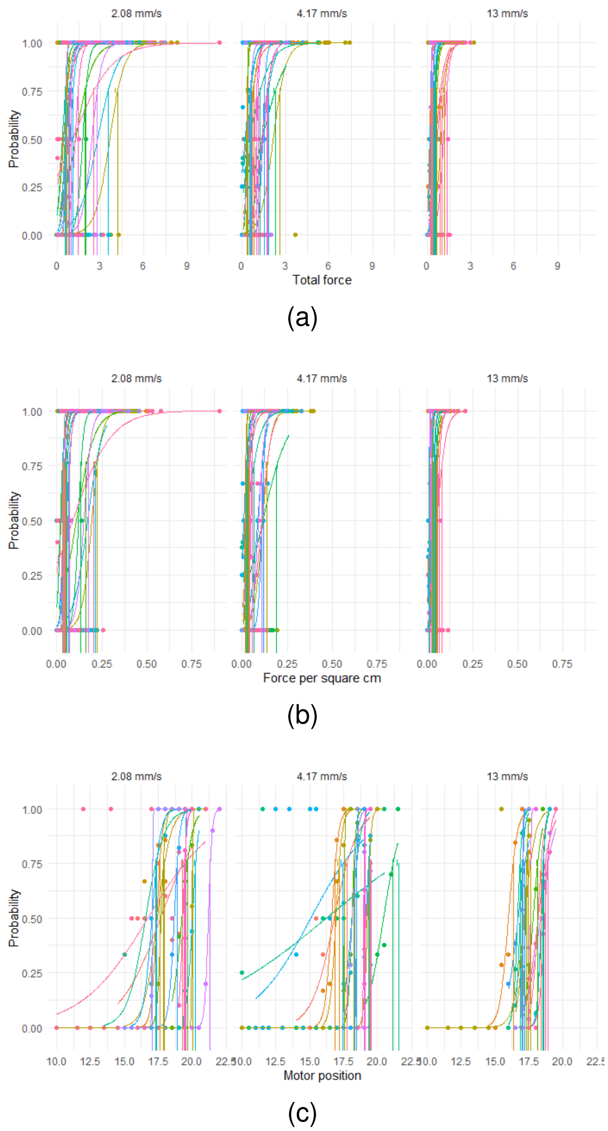

Figure 2: Above we see psychometric curves for each participant per actuation speed condition for (a) the normal force, (b) pressure and (c) motor position. The curves give an indication of sensitivity (slope steepness), and bias (distance from midpoint).

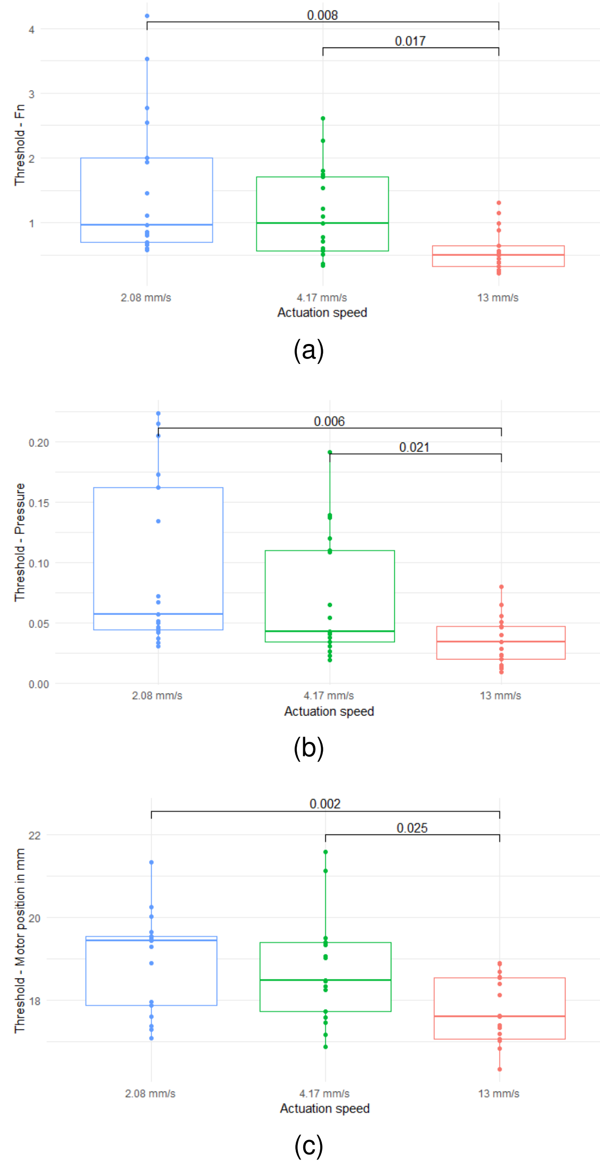

Figure 3: Above we see three boxplots per actuation speed condition for (a) the normal force, (b) pressure and (c) motor position. In all the figures the dots indicate individual participants, the colours the actuation speed conditions, the lines above the boxplots are accompanied by significant p-values found when comparing the conditions.

in mm from the starting point, see Figure 2c. We compared the motor positions to investigate if there was a difference in the reduction of the ribbon length, and thus a difference in indentation on the arm, between the conditions.

B. Descriptive statistics

The threshold means for the normal force are a mean of 1.54 N (Median = 0.964 N, SD = 1.12 N) for 2.08 mm/s, a mean of 1.13 N (Median = 0.983 N, SD = 0.704 N) for 4.17 mm/s and a mean of 0.564 N (Median = 0.496 N, SD = 0.334 N) for 13 mm/s. The means for force per square cm are a mean of 0.0969 N (Median = 0.0575 N, SD = 0.0711) for 2.08 mm/s, a mean of 0.072 N (Median = 0.0432 N, SD = 0.0517 N) for 4.17 mm/s and a mean of 0.0353 N (Median = 0.0342 N, SD = 0.0201 N) for 13 mm/s. The means and medians for the motor position in mm from the starting position. We found 18.95 mm (Median = 19.45 mm, SD = 1.2 mm) for 2.08 mm/s, a mean of 18.75 mm (Median = 18.5 mm, SD = 1.29 mm) for 4.17 mm/s and a mean of 17.7 mm (Median = 17.6 mm, SD = 0.81 mm) for 13 mm/s. The box plots in Figure 3 give an indication of the data distribution.

C. Comparison

The two separate ANOVAs showed a significant effect of contraction speed on threshold of the normal force: $F(2, 32) = 10.42$, p-corrected $< .002$; threshold of the pressure force per square cm: $F(2, 32) = 10.00$, $p < .001$. The Friedman test showed a significant effect of threshold of the motor position: $X^2(2) = 22.24$, p = $< .001$. The post-hoc analyses are reported in Figure 3.

IV. Discussion

Our results indicate that a lower actuation speed of the motorized ribbon increases the perception threshold in terms of normal force, pressure and reduction around the arm. The answer to research question: ”To what degree does actuation speed influence the perception threshold for pressure stimuli by a textile actuator on the lower arm?” is that the actuation speed does influence the perception threshold of a pressure stimulus. However, to find the exact relationship between actuation speed and threshold more research is required.

Results for the two slowest conditions are similar, despite one being twice as slow as the other. This indicates a ceiling or plateau, and thus a non-linear relationship between actuation speed and perception threshold. The exact relationship is unclear at the moment of writing. To find the function of this relationship further research is required. We propose a study similar to the one presented in this paper with actuation speed conditions between 13 mm/s and 4.17 mm/s to find the critical range in which there is a tradeoff between actuation speed and threshold.

The three dependent variables in this study are: pressure (force per square cm), total normal force and indentation. The results are similar for all independent variables. This indicates that the independent variables in have a similar relationship with actuation speed. Thus we would expect the same in the study proposed above.

A. Mechanoreceptors

A relevant question is why actuation speed has an effect on the perception threshold. We postulate two mechanisms that may play a role and can be linked to the mechanoreceptors in the arm. Firstly, the fact that speed matters indicates that the perceptual system integrates over time. This is a known phenomenon, e.g. temporal summation is the mechanism responsible for increased subjective intensity or lower thresholds of stimuli with a longer duration. The autors of [23] wrote that temporal summation for vibratory stimuli occurs in the Pacianian channel, while no evidence was found for temporal summation in the NP I and NP II channels. Our finding, a higher threshold for the slower two stimuli, contradicts with [23]. A limited time frame in which a stimulus can integrate could be a possible explanation for this contradiction.

A second possible mechanism is related to mechanical properties of the skin, which cause the indentation area to be dependent on the indentation speed. Or more precisely: the area of indentation might be larger for larger actuation speeds. This effect means that larger speeds may activate a larger population of mechanoreceptors. In [13] the authors found a progressive spatial recruitment of receptors when their stimuli increased in force and speed.

The responses of mechanoreceptors to various stimuli can provide additional insight in the effect of actuation speed on the perception of pressure stimuli. Most touch stimuli cause a response in multiple populations and various types of mechanoreceptive afferents [11], [14]. It is probable that the squeezing stimulus by our set-up also provokes multiple mechanoreceptor types. SA and RA receptors respond differently to various actuation speeds of suprathreshold, stretch stimuli on the hairy skin of humans [12] and indentation stimuli on the glabrous skin of the macaque [13]. Namely, the RA mechanoreceptors do not respond to slow stimuli while the SA receptors respond to both slow and fast stimuli.

We speculate that; (1) our fastest stimuli integrated more over time than the two slowest stimuli, (2) stimuli of higher forces and speeds recruit a larger population of mechanoreceptors, (3) the RA receptors do not respond at a lower speed. These factors together causing a higher threshold of low speed stimuli.

B. Set-up

The actuation speed of the motorized ribbon is controlled with delays between motors steps via Arduino. In preliminary testing and after we experienced no jitter. There are multiple other ways to control the actuation speed of a servo motor besides adding delays between motor step, namely: with a motor controller board or a linear actuator control board, by adjusting input voltage and by using separate motors with different gearing specifications [24]. To our knowledge, there is no literature suggesting that any of these methods disrupt temporal summation. However, to gain further insight in these different methods for controlling actuation speed and a possible effect on actuation speed, this study should be repeated with different set-ups that control the speed in the varying ways mentioned.

C. Implications

Our results mean that in haptic interaction design, we need to take higher thresholds for slower actuation into account. To mitigate this haptic interactions with slow actuation speed could be designed with higher forces. In other words: actuators that are slow should be able to deliver a higher force. Actuators that are slower are suitable for use cases where a delayed or slower actuation is not a problem or even preferred. For example, in mediated social touch, a slow and increasing warning, or a slow squeeze as a way to calm the user down.

D. Limitations

The conditions in this study only cover a limited range of speed. The two lowest speed conditions show no effect when compared. Thus we currently cannot conclude what the critical range of actuation speed is. We could get a clearer picture about the effect of actuation speed on the perception threshold of pressure by including conditions in a future study that are between our fastest and middle condition.

The age range of the study is limited. The mechanical characteristics of our skin changes as we age. If skin morphology is part of the explanation of the effect of speed on the perception threshold of pressure, age could matter. This has to be addressed in a follow up study.

E. Future analysis

The rates of application (10 g/s, 15 g/s and 30 g/s) in [15] cover a smaller range than the rates (1, 10, and 100 g/s), which could explain the different results between the two studies. Where [15] found no difference in perceived magnitude while [13] does. The results from [13], [15] are indirectly related to our results. Rate of force application is related to application speed. To make a direct comparison between the previous results and those found with the motorized ribbon, the relationship between actuation speed and rate of force application needs to be linear. Currently, this is unknown.

Therefore, further investigation is required to find the relationship between the perception threshold, perceived magnitude and actuation speed. A proposal for future research is to investigate the effect of application speed on perception threshold and magnitude perception with the same set-up and same application speed conditions.

V. Conclusion

Our results indicate that actuation speed influences the perception threshold in terms of normal force, pressure and indentation. Namely, the faster the actuation of the stimulus the lower the threshold. This is possibly due to two effects:integration over time in the perceptual system (i.e. more integration for faster actuation), and altered area of indentation due to skin morphology (i.e. increased area of indentation for faster actuation). We relate our findings to the firing responses of varying mechanoreceptors during such a mechanical stimulation. At lower actuation speeds, RA receptors do not fire reliably, like they do at higher speeds for suprathreshold stimuli while SA receptors do fire at low and high speeds. Thus, we think that at lower speeds only the SA receptors are responsible for the perception of our squeezing stimulus, causing a higher threshold than at higher speeds where RA receptors together with SA receptors are responsible for the perception of a squeezing stimulus. These findings have implications for the design of haptic actuators and haptic interaction design. Namely, when designing a new actuator, the engineer has to take into account that at certain low speeds actuation speed and threshold are a tradeoff. In case of haptic interaction design, to design a perceivable pressure stimulus of a low speed, force and indentation must be higher to compensate for the higher perception thresholds. These implications apply to the use case of mediated social touch. Where future research should also address the possible effects of actuation speed on comfort and social interpretation of the touch to determine suitable actuation speeds. In addition, future research should replicate the study with various set-ups and other modalities, as that may give further insight into the effect of actuation speed on perception. Other body locations, like the upper arm and shoulder, are also relevant for mediating passive social touch and should be investigated.

References

[1] "Feelhey – hey." [Online]. Available: https://feelhey.com/

[2] J. Weda, D. Kolesnyk, A. Mader, and J. van Erp, "Experiencing touch by technology," in *Haptics: Science, Technology, Applications: 13th International Conference on Human Haptic Sensing and Touch Enabled Computer Applications, EuroHaptics 2022, Hamburg, Germany, May 22–25, 2022, Proceedings*. Springer Nature, p. 110.

[3] 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)*, Conference Proceedings, pp. 193–198.

[4] A. Gupta, A. A. R. Irudayaraj, and R. Balakrishnan, "Hapticclench: Investigating squeeze sensations using memory alloys," in *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, 2017, pp. 109–117.

[5] 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.

[6] M. Zhu, T. N. Do, E. Hawkes, and Y. Visell, "Fluidic fabric muscle sheets for wearable and soft robotics," *Soft robotics*, vol. 7, no. 2, pp. 179–197, 2020.

[7] P. T. Phan, M. T. Thai, T. T. Hoang, J. Davies, C. C. Nguyen, H.-P. Phan, N. H. Lovell, and T. N. Do, "Smart textiles using fluid-driven artificial muscle fibers," *Scientific reports*, vol. 12, no. 1, pp. 1–15, 2022.

[8] 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.

[9] G. Corniani and H. P. Saal, "Tactile innervation densities across the whole body," *Journal of Neurophysiology*, vol. 124, no. 4, pp. 1229–1240, 2020.

[10] K. O. Johnson, "The roles and functions of cutaneous mechanoreceptors," *Curr Opin Neurobiol*, vol. 11, no. 4, pp. 455–61, 2001, johnson, K O Journal Article Review England Curr Opin Neurobiol. 2001 Aug;11(4):455-61. doi: 10.1016/s0959-4388(00)00234-8.

[11] S. J. Bensmaia, "Tactile intensity and population codes," *Behavioural brain research*, vol. 190, no. 2, pp. 165–173, 2008.

[12] B. B. Edin, "Quantitative analyses of dynamic strain sensitivity in human skin mechanoreceptors," *Journal of neurophysiology*, vol. 92, no. 6, pp. 3233–3243, 2004.

[13] R. H. Cohen and C. J. Vierck, "Population estimates for responses of cutaneous mechanoreceptors to a vertically indenting probe on the glabrous skin of monkeys," *Experimental brain research*, vol. 94, no. 1, pp. 105–119, 1993.

[14] ——, "Relationships between touch sensations and estimated population responses of peripheral afferent mechanoreceptors," *Experimental brain research*, vol. 94, no. 1, pp. 120–130, 1993.

[15] M. Paré, H. Carnahan, and A. M. Smith, "Magnitude estimation of tangential force applied to the fingerpad," *Experimental Brain Research*, vol. 142, no. 3, pp. 342–348, 2002.

[16] A. Guzererler, W. R. Provancher, and C. Basdogan, "Perception of skin stretch applied to palm: Effects of speed and displacement," in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2016, pp. 180–189.

[17] A. Manasrah and S. Alkhalil, "A 2-dof skin stretch display on palm: Effect of stimulation shape, speed and intensity," in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2020, pp. 12–24.

[18] "Home." [Online]. Available: https://www.arduino.cc/

[19] 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.

[20] 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.

[21] J. Peirce, J. R. Gray, S. Simpson, M. MacAskill, R. Höchenberger, H. Sogo, E. Kastman, and J. K. Lindeløv, "Psychopy2: Experiments in behavior made easy," *Behavior research methods*, vol. 51, no. 1, pp. 195–203, 2019.

[22] 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

[23] G. A. Gescheider, S. J. Bolanowski, and R. T. Verrillo, "Some characteristics of tactile channels," *Behavioural brain research*, vol. 148, no. 1-2, pp. 35–40, 2004.

[24] "How to adjust linear actuator speed." [Online]. Available: https://www.actuonix.com/adjust-linear-actuator-speed