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Perceived Intensity of Pneumatic Vibrotactile Stimuli: Effects of Pressure, Frequency, and Stiffness

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***Abstract*—Vibrotactile actuators are used in many different haptic devices, e.g. game controllers and smartphones. These vibrotactile actuators are typically made of rigid materials. In this paper, we use soft pneumatic actuators known as Pneumatic Unit Cell (PUC) to characterize the perceived intensity of vibrotactile stimuli when presented at the tip of the index finger. This study investigates how three parameters—stimulus pressure (4 to 30 kPa), inflation-deflation frequency (20 to 100 Hz), and actuator stiffness (determined by top layer thicknesses of 0.9 mm and 1.2 mm)—influence the perceptual intensity of the stimuli. Psychophysical experiments involving 16 participants were conducted using the AEPsych toolbox. These reveal that all the three parameters - pressure, frequency, and actuator stiffness significantly affect perceptual intensity. The findings indicate that both pressure and frequency exhibit a positive main effect and a positive interaction effect on perceived vibrotactile intensity. Additionally, the results show that, for a given frequency, pressure variations produce more perceptually distinct stimuli than frequency variations for a given pressure. Finally, presenting vibrotactile stimuli on a less stiff PUC actuator was perceived as being less intense than when the same stimulus was presented on a stiffer PUC actuator. Overall, this study provides key insights into the combined influence of pressure, frequency and actuator stiffness on the perceived vibrotactile intensity.**

***Index Terms*—Perceptual intensity, Soft actuators, Haptics, Vibrotactile**

I. INTRODUCTION

TACTILE interaction allows humans to interpret the physical world through touch. These interpretations include properties such as compliance, roughness, temperature, and friction [1]. Humans often evaluate these properties using qualitative terms like ”low,” ”medium,” and ”high,” or modifiers such as ”very” to express the intensity of tactile perception. For instance, terms like ”rough” and ”very rough” reflect differences in the perceived intensity of surface texture. Such detailed perceptions provide a rich and informative understanding of the world around us. Understanding how to evoke these nuanced tactile experiences can aid in the design of intuitive haptic interfaces.

In the field of haptics, vibrotactile stimuli delivered through electromechanical devices are among the most widely used and well-understood methods for providing tactile feedback [2]. In their work, [3] explored the perceptual aspects of commonly used vibrotactile devices to support the design of intuitive user experiences. The perceived intensity of a vibrotactile stimulus defined as the subjective sensation of its strength. This perception is influenced by multiple factors, including vibration frequency [4], [5], amplitude [5], [6], [7], [8], contact area [9], body site [9], stimulus duration [10], and age [11]. [6] demonstrated that the perceived intensity of a 60 Hz vibrotactile stimulus increases as vibration amplitude increases. Subsequent studies by [7] and [8] extended these findings, revealing a positive correlation between vibration amplitude and perceived intensity across a broader frequency range (25 Hz to 700 Hz).

In terms of frequency, [4] examined the perceived intensity of vibrotactile stimuli at 60 Hz and 250 Hz, highlighting the influence of frequency on perception. Their findings indicate that for a given amplitude, a 250 Hz stimulus was perceived as more intense than a 60 Hz stimulus. However, the rate of increase in perceived intensity with increasing amplitude was greater for the 60 Hz stimulus compared to the 250 Hz stimulus. Supporting these psychophysical findings, a physiological study by [12] demonstrated a consistent relationship between stimulus strength and mechanoreceptor response potentials, further validating the interplay between amplitude, frequency, and perceived intensity. In addition, [5] demonstrated that combining variations in both amplitude and frequency yields more perceptually distinguishable vibrotactile stimuli than when only one parameter varies (e.g., fixed amplitude with varying frequency or fixed frequency with varying amplitude). This suggests the presence of an interaction effect between amplitude and frequency for vibrotactile stimuli.

While these previous studies used electromechanical actuators, pneumatically driven soft actuators are a new class of actuators which also demonstrate the ability to deliver vibrotactile stimuli [13], [14], [15], [16], [17], [18], [19]. These actuators offer unique advantages, including design flexibility, the ability to conform to the human body due

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This work involved human subjects in its research. Approval of all ethical and experimental procedures and protocols was granted by Ethics Review Board of Eindhoven University of Technology under Application No. ERB2024ME6.

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to their soft material composition, and a high power-to-weight ratio, making them a compelling option for vibrotactile feedback [17], [20], [21]. In this study, we characterize the perceived intensity of vibrotactile stimuli when delivered through a soft pneumatic actuator. As implied by the name, soft actuators are structurally compliant, which depends on both the material hardness and the actuator's design [13]. Prior work [13] has demonstrated how actuator design influences the mechanical behavior of soft actuators. Based on these findings, further exploration of how actuator stiffness affects the perceived intensity of vibrotactile stimuli is warranted.

Psychophysics studies are often performed to evaluate perceived vibrotactile intensity. Conventional psychophysical methods for mapping perceptual intensities typically rely on intensity matching either within or across modalities, where participants adjust or compare the perceived intensity of a test stimulus to a known reference, either within the same sensory modality (e.g., vibrotactile to vibrotactile) or across different modalities (e.g., vibrotactile to auditory). Alternatively, direct scaling methods allow participants to assign numerical values to perceived intensities based on their subjective experience, often following a ratio scale without predefined categories. These methods have been shown to yield comparable results [22]; however, their applicability becomes impractical when evaluating the perceived intensity of a larger array of test stimuli, as this would result in an impractically large number of comparisons.

As an alternative to address these limitations [23] proposed a non-parametric Bayesian approach implemented through the Adaptive Experimentation in Psychophysics (AEPsych) toolbox. The AEPsych toolbox leverages real-time adaptive sampling techniques to efficiently explore the parameter space. A cost (acquisition) function guides this process, prioritizing regions most likely to enhance understanding of perceptual intensity. Using a Gaussian process model, the toolbox fits the sampled data points to match the internal magnitude function (latent function) that individuals use to evaluate perceptual intensity. An early version of this method tested in practice by [24] by studying the relationship between the properties of a vibrotactile stimulus and the perceived hardness of an object in a virtual setting. Browder et al. [24] evaluated the AEPsych toolbox against traditional psychometric methods using a non-parametric Bayesian model with Gaussian process priors. Their approach accurately predicted results from a second dataset and revealed subtle perceptual effects, such as nonlinear trends at low decay constants, demonstrating that model-based methods implemented in AEPsych toolbox can reliably estimate perceptual judgments with fewer trials.

In this study Pneumatic Unit Cell (PUC) actuators (Fig.1a) are used to investigate the influence of pressure, frequency and actuator stiffness on perceived vibrotactile intensity, which refers to the subjective strength of the vibrotactile stimulus as experienced by the participants. These soft actuators were first introduced by [25] to explore their potential as haptic feedback interfaces in virtual reality (VR) tasks. A subsequent study by [13] examined the input-output characteristics of PUC actuators under varying pressure, frequency, and actuator stiffness conditions. The study revealed that amplitude is proportional to applied pressure, while higher frequencies and increased stiffness negatively affect amplitude. In this study, it is hypothesized that as pressure increases, perceived vibrotactile intensity will also increase. Similarly, as frequency increases, perceived vibrotactile intensity is expected to rise. Additionally, pressure and frequency are hypothesized to have a positive interaction effect on perceived vibrotactile intensity. Finally, the stiffness of the PUC actuator is expected to negatively influence the perceived vibrotactile intensity. The following sections of this paper describe the materials and methodology used to measure the perceived vibrotactile intensity of the participants, the analysis followed to evaluate the hypotheses, this is followed by the results, discussions and conclusions. By examining the effects of pressure, frequency, and actuator stiffness on perceived vibrotactile intensity, this study provides insights that can guide the design of an intuitive rendering of vibrotactile stimulus.

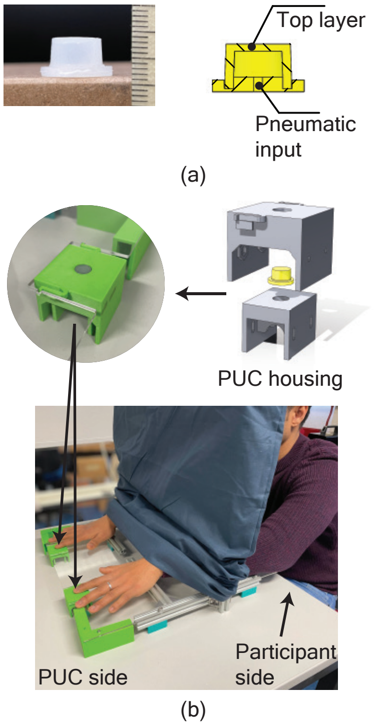


Fig. 1. (a) Fully fabricated Pneumatic Unit Cell (PUC) actuator as shown next to a reference scale (left), schematic overview of the PUC actuator, highlighting the pneumatic input and the top layer of the actuator (right). PUC actuators with 0.9 mm and 1.2 mm top layer thickness were the focus of the current study. (b) Experimental setup for studying perceptual vibrotactile intensity. The setup includes a fabric curtain separating the 'Participant side' and the 'PUC side', so that the participants could not see the actuators. The image also highlights the housing of the PUC actuator, designed to keep the PUCs in place.

II. MATERIAL AND METHOD

A. Participants

The experiment involved sixteen participants (fourteen male, two female) aged 26–35. Fourteen were right-handed, and two were left-handed. All participants volunteered, reported no sensory or motor issues, and had no prior knowledge of the experimental design. The study was approved by the Ethics Review Board of Eindhoven University of Technology (ERB2024ME6). All participants were given time to review the informed consent form, and the experimenter verbally reiterated its contents to ensure understanding. All participants signed informed consent forms prior to participation.

B. Pneumatic Unit Cell (PUC) Actuator

In this study, two Pneumatic Unit Cell (PUC) actuators with differing stiffness levels were used to investigate perceived vibrotactile intensity. The variation in stiffness was achieved by modifying the thickness of the top layer: one design featured a 0.9 mm thick top layer, while the other had a 1.2 mm thick top layer, with the latter being stiffer due to its increased thickness (Fig. 1a). Hereafter, these will be referred to as the 0.9 mm PUC actuator and the 1.2 mm PUC actuator, respectively. Both actuator designs were fabricated using Dragon Skin$^{\text{TM}}$ 10 Medium, following a close-mold fabrication technique to maintain dimensional consistency. Detailed steps for the fabrication and characterization of the actuators can be found in [13].

C. Hardware Setup

We employed Soft a Robotics Control Unit (SRC) [26] to drive the PUC actuators (identical to the setup reported in [13]). The setup consists of two main components: a proportional pressure-control valve (VEAB-L-26-D13-Q4-V1-1R1, Festo, Esslingen, Germany) to regulate pneumatic pressure, and a high-frequency valve (MHP2-MS1H-3/2G-M5, Festo, Esslingen, Germany) to control the frequency at which the pressure inlet to the actuator opens and closes. Both the pressure regulator and the high-frequency valve were controlled via a Raspberry Pi-Matlab interface.

A desktop experimental setup was fabricated for the study (Fig. 1b), measuring $500 \times 450 \times 400, \text{mm}^3$. The setup consisted of two sections: the 'PUC side', where the PUC actuators were positioned, and the 'participant side', where participants were seated. These sections were separated by a fabric curtain to prevent visual cues during the experiment. The base of the setup was fitted with an acrylic sheet, allowing participants to rest their forearms. The actuators were enclosed in a rigid, 3D-printed housing, designed to keep the top layer of the PUC actuators flush with the base. This design ensured that participants did not inadvertently apply force on the top of the PUC during the experiment. Placeholders were incorporated into the base on the 'PUC side' to hold the actuator housing in position (Fig. 1b).

D. Experimental Design

A psychophysical experiment was conducted in two individual modules to measure the influence of pressure, frequency, and stiffness of PUC actuators on the perceived vibrotactile intensity. In the first module, referred to as intensity mapping, the perceived intensities of the 0.9 mm and 1.2 mm PUC actuators were mapped independently. A two-alternative forced-choice (2AFC) method was used to create the intensity map. Pressure and frequency were used as independent variables to investigate the Influence on the perceived intensity of vibrotactile stimuli for each actuator design. Participants performed a total of 100 comparisons to map the perceived vibrotactile intensity for a given PUC design. For the 0.9 mm actuator, two identical 0.9 mm actuators were positioned on the 'PUC side' of the experimental setup (Fig. 1b). The same experimental procedure was repeated for the 1.2 mm actuator, with two identical 1.2 mm actuators placed on the 'PUC side'. Fig. 2 illustrates the PUCs used in mapping perceived vibrotactile intensity.

The second module, referred to as Level Set Estimate, aimed to identify the pressure-frequency combinations of the 1.2 mm PUC actuator that were perceptually equal in intensity to a reference stimulus [17 kPa, 60 Hz] delivered via a 0.9 mm actuator. Pressure and frequency were again used as independent variables in identifying the pressure-frequency combinations that are perceived as equally intense as the reference stimulus. A two-alternative forced-choice (2AFC) method was again used in identifying the pressure-frequency combinations. At the start of the module, a 0.9 mm PUC actuator was positioned on the right-hand side, while a 1.2 mm PUC actuator was placed on the left-hand side of the "PUC side" of the experimental setup. The positions of these actuators were switched every 10 trials. Fig. 2 illustrates the arrangement of the PUCs used in the second module. This module consisted of 80 trials. To minimize bias, the order of the modules was counterbalanced between participants.

E. Protocol

During the experiment, participants were seated on the 'participant side' of the setup and were introduced to the equipment, which included a monitor displaying the Participant Graphical User Interface (GUI) and a noise-canceling headset. They were instructed to rest their forearms on the acrylic sheet and extend their hands through the curtain partition to the 'PUC side' of the setup. With assistance from the experimenter if needed, participants positioned their index fingers on top of the PUC actuators. To minimize distractions, headphones played white noise throughout the experiment. Text cues on the Participant GUI informed participants of the trial's status.

After being properly positioned and familiarized with the setup, participants began the experiment. As illustrated in Fig. 2, each trial consisted of two stimuli presented sequentially, with each stimulus lasting one second, with a two-second pause in between. After both stimuli were

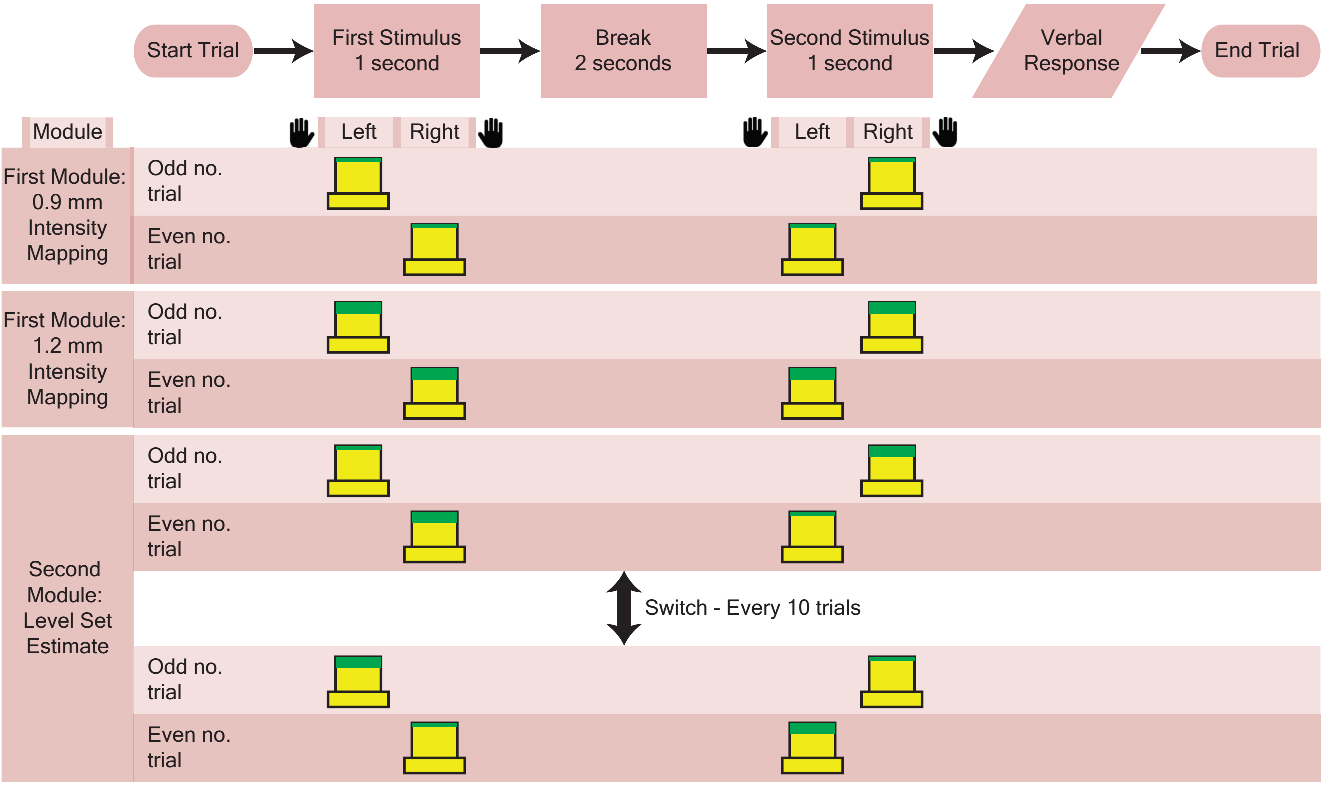


Fig. 2. A schematic representation of the experimental protocol, illustrating the sequence of vibrotactile stimulus presentation in both the intensity mapping module and the level set estimation module. At the top the sequence of a trial can be seen, while the different rows show the details for that specific module during each step of the trial sequence. For example, in the first module, mapping perceived vibrotactile intensity of 0.9 mm PUC actuator, an odd-numbered trial presents the first stimulus to the left-hand index finger and the second to the right-hand index finger. In an even-numbered trial, the order is reversed, with the first stimulus presented to the right-hand index finger and the second to the left-hand index finger.

presented, participants verbally responded ’left’ or ’right’ to the question displayed on the Participant GUI: ’Which of the two stimuli is perceptually the most intense? Left or Right?’ The experimenter manually recorded the response, marking the end of the trial. In each module, the first stimulus of trial 1 was always presented to the left index finger. In subsequent trials, the order of the first stimulus alternated between the left and right index fingers across trials. Participants were given 1 to 2 minutes of break after every 35 trials. The experiment was conducted over two separate modules, each lasting approximately one hour.

F. AEPsych Toolbox Configuration

The AEPsych toolbox [23], which employs a non-parametric Bayesian approach, was used to map perceived vibrotactile intensity. A detailed explanation of the toolbox’s working principles is provided in literature [27], [28]. The toolbox models a latent function $F(x)$, where $x \in \mathcal{R}^2$ represents the parameter domain defined by the pressure and frequency magnitudes of the stimulus. The latent function F captures the internal magnitude function used by the participant in judging the vibrotactile stimulus intensity, This latent function is inferred from the participant’s responses to the two-alternative forced-choice trials.

Different configurations of the AEPsych toolbox were applied across two modules in the study. The first module aimed to map perceived intensity across the pressure-frequency parameter space, accomplished by configuring the toolbox for global exploration. This exploration was implemented using two strategies: (1) an initialization strategy, which employed the Pairwise Sobol Generator to perform 10 random comparisons within the parameter space, and (2) an optimization strategy, which generated 90 additional comparisons. The total number of trials was determined based on the reduction of model uncertainty, as informed by pilot studies. The optimization strategy utilized a Pairwise Probit model as the link function and the Pairwise-Optimize-Acqf Generator with q-Noisy Expected Improvement as the acquisition function to recommend pairs of stimuli for each trial. For every five trials, the toolbox refitted the model using all accumulated data. The updated model was then used to recommend the next five trials, enabling iterative refinement throughout the module.

The gathered data from each participant was used to estimate a latent function F_{Map}, which represents the internal magnitude scaling followed by the respective participant in scaling vibrotactile intensity. The estimated magnitude (posterior mean) of the perceived intensity was reported on a relative scale with respect to a reference stimulus [28]. In this study, the reference stimulus (x_{ref}) was set at [17 kPa, 60 Hz], chosen for its central position within the pressure–frequency parameter space. The latent function F_{Map} was then used to estimate the perceived intensity at unsampled locations x_{new} of the pressure-frequency parameter space.

To create a complete perceived intensity map of the pressure-frequency parameter space, the space was discretized into a 50 × 50 grid, providing a balance between computational efficiency and resolution. The posterior means at each grid point were predicted based on each participant's estimated F_{Map}. A typical example of a posterior mean maps, representing the perceived vibrotactile intensity for each participant relative to their own perceived intensity of the reference stimulus ([17 kPa, 60 Hz]), is shown in Fig. 3.

In the second module of the study, the goal was to compare the perceived intensity between different PUC actuator designs. Specifically, the study aimed to identify pressure-frequency combinations of a 1.2 mm PUC actuator that were perceived as equally intense as a reference stimulus from a 0.9 mm PUC actuator. This was achieved by configuring the AEPsych toolbox for a Level Set Estimation (LSE) with a target level of 50%. The LSE study was also conducted using two strategies: an initialization strategy and an optimization strategy. The initialization strategy involved generating 10 random trials using the Sobol Generator. The optimization strategy then added 70 more comparisons. The total number of trials was determined based on the reduction of model uncertainty, as informed by pilot studies. The optimization strategy employed GP Classification as the link function and the Optimize-Acqf Generator with GlobalMI as the acquisition function.

Similar to the iterative fitting approach used in the first module, the LSE model was refitted every five trials using all accumulated data. The updated model was then used to recommend the next five trials. The fitted latent function F_{LSE}, followed the same paradigm as F_{map}. However, it differed in its reference stimulus, which was defined as [17 kPa, 60 Hz] on a 0.9 mm PUC actuator for F_{LSE}. Furthermore, F_{LSE} was constructed with the objective of minimizing uncertainty only around the pressure-frequency pairs that met the 50% criterion.

The LSE map for each participant was constructed using participant's comparison data to estimate a latent function, F_{LSE}. To generate a complete map of the parameter space, the space was discretized into 50 × 50 grid, a resolution chosen to balance computational efficiency and precision. At each grid point, the preference was evaluated using the participant's estimated F_{LSE}. The toolbox then identified pressure-frequency combinations that were perceptually similar to the reference stimulus, represented by the 50% contour line in Fig. 4.

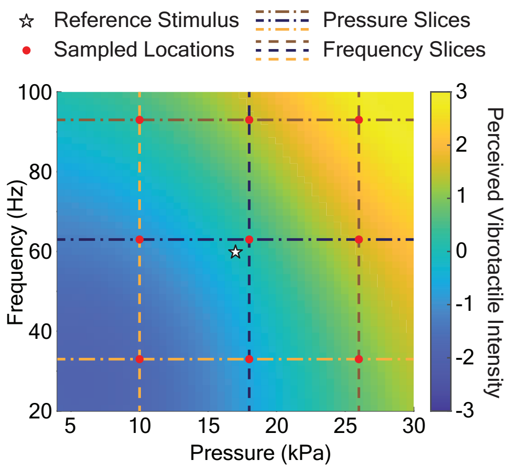


Fig. 3. Example map of a participant from the intensity mapping module, expressed as using posterior means. The white star marks the reference stimulus, x_{ref} [17 kPa, 60 Hz]. Negative posterior mean values represent perceived intensities lower than x_{ref}, while positive values represent greater intensities. Red dots indicate sampled parameter space locations used to assess the main effects of pressure and frequency on perceived vibrotactile intensity. Dashed lines represent frequency slices, and dash-dot lines represent pressure slices used to analyze the interaction effect between pressure and frequency.

G. Analysis - First module: Intensity Mapping

For each participant, two separate perceived vibrotactile intensity maps were generated—one for the 0.9 mm PUC actuator and another for the 1.2 mm PUC actuator. Each map was built based on 100 comparisons. While most participants completed the full set of comparisons, technical issues led to minor deviations for two participants. Specifically, one

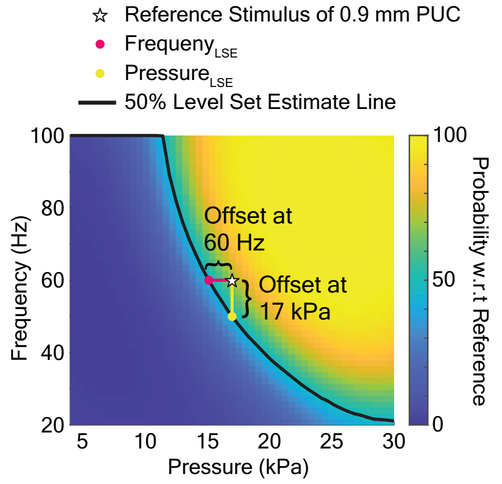


Fig. 4. An example LSE map from the level set estimate module is shown. The star represents the reference stimulus at [17 kPa, 60 Hz], delivered using the 0.9 mm PUC actuator. The black line indicates the pressure-frequency combinations of the 1.2 mm PUC actuator that produce the same perceived intensity as the reference stimulus. In this case, $\text{Frequency}_{\text{LSE}}$ refers to the frequency at 17 kPa, and $\text{Pressure}_{\text{LSE}}$ refers to the pressure at 60 Hz, both adjusted to match the perceived intensity of the reference stimulus. Here, $\text{Frequency}_{\text{LSE}}$ is lower than 60 Hz, and $\text{Pressure}_{\text{LSE}}$ is lower than 17 kPa.

participant completed 94 comparisons for the 0.9 mm PUC intensity map, and another completed 88 comparisons for the 1.2 mm PUC intensity map.

1) Effect of Pressure and Frequency: The posterior mean was used to evaluate the main effect of pressure and frequency on perceived vibrotactile intensity for a given PUC design. Posterior means were sampled at nine evenly distributed points within the parameter space to provide a representative overview of the intensity maps. These points, centered around [18 kPa, 63 Hz], were [10 kPa, 33 Hz], [18 kPa, 33 Hz], [26 kPa, 33 Hz], [10 kPa, 63 Hz], [18 kPa, 63 Hz], [26 kPa, 63 Hz], [10 kPa, 93 Hz], [18 kPa, 93 Hz], and [26 kPa, 93 Hz], and are represented as red dots in Fig. 3. The posterior means from these nine locations were used to perform a 3 (pressure) $\times$ 3 (frequency) repeated-measured Analysis of Variance (ANOVA) for each design.

2) Interaction Between Pressure and Frequency: To analyze the combined influence of pressure and frequency on perceived vibrotactile intensity for a given design, the number of perceptually distinct stimuli, i.e., Just Noticeable Differences (JNDs), were used as the metric. In this context, a JND is defined as the point where there is a 75% probability of perceiving a comparison stimulus as being more intense than a reference stimulus.

To calculate the number of JNDs within the measured range, the posterior means obtained in Section II-F needed to be expressed in the probability domain, representing the likelihood of choosing one stimulus (x_{new}) over a reference stimulus (x_{ref}). Since the posterior means are measured on a relative scale, they inherently encode this probabilistic information. The AEPsych toolbox models the net difference between x_{new} and x_{ref} as following a standard normal distribution, $N(0,1)$ and computes the JNDs based on the cumulative distribution function (CDF). In a standard normal distribution $N(0,1)$, a probability of 75% on the CDF corresponds to a difference of 0.67 in posterior means.

To study the interaction effect, two sets of three slices, oriented differently, were selected. The first set, referred to as pressure slices, was taken parallel to the pressure axis of the parameter space and sampled at frequencies of 33 Hz, 63 Hz, and 93 Hz. The second set, referred to as frequency slices, was taken parallel to the frequency axis and sampled at pressures of 10 kPa, 18 kPa, and 26 kPa (Fig. 3). To calculate the number of JNDs for these slices, the range of posterior means along that slice was measured and divided by 0.67. This process was repeated for the three pressure slices and the three frequency slices, yielding three JND values for each set of slices.

To statistically test the combined influence of pressure and frequency on perceived vibrotactile intensity, two individual one-way repeated-measured ANOVA tests per design were conducted. The first, referred to as the pressure slice ANOVA, compares the number of JNDs across the three pressure slices obtained from all participants. The second, referred to as the frequency slice ANOVA, compares the number of JNDs across the three frequency slices obtained from all participants.

JNDs were also used to analyze if one of the factors pressure or frequency had a greater influence on perceived vibrotactile intensity than the other. To evaluate this, the mean of JNDs measured across pressure slices (at frequencies 33 Hz, 63 Hz, and 93 Hz) was compared to the mean of JNDs measured across frequency slices (at pressures 10 kPa, 18 kPa, and 26 kPa). A paired t-test was performed on the 0.9 mm PUC data to compare the mean of the JNDs from pressure slices with those from frequency slices across all participants. For the 1.2 mm PUC data, a Wilcoxon signed rank test was used instead, as the data did not meet the normality assumption.

H. Analysis - Second module: Level Set Estimate

For each participant, one LSE map were generated. Each map was built based on 80 comparisons. While most participants completed the full set of comparisons, technical issues led to minor deviations for three participants. Specifically, two participant completed 55 comparisons, and another completed 62 comparisons.

To analyze the influence of stiffness on perceptual intensity, we evaluated the level set estimate (LSE) lines (Fig. 4), which represent pressure-frequency combinations presented using the 1.2 mm PUC actuator that produce a similar perceptual intensity to the reference stimulus [17 kPa, 60 Hz] presented using the 0.9 mm PUC actuator. The analysis considered two scenarios: (1) a shift in frequency at 17 kPa from 60 Hz on the 1.2 mm actuator to match the reference intensity, and (2) a shift in pressure at 60 Hz from 17 kPa to achieve the same intensity. These shifts quantify the adjustments required in pressure or frequency for the 1.2 mm actuator to replicate the perceived intensity of the reference stimulus.

To evaluate the frequency and pressure shifts required to match the reference intensity, we analyzed deviations from 60 Hz and 17 kPa, respectively, on the 1.2 mm PUC actuator. For frequency, we examined the deviation from 60 Hz at 17 kPa by identifying each participant's $Frequency_{LSE}$ from the LSE lines (Fig. 4) and calculating the shift as the difference between $Frequency_{LSE}$ and 60 Hz. Similarly, for pressure, we analyzed the deviation from 17 kPa at 60 Hz by identifying each participant's $Pressure_{LSE}$ and calculating the shift as the difference between $Pressure_{LSE}$ and 17 kPa. In both cases, a Student's t-test was performed to determine whether the mean shift significantly differed from zero.

III. RESULTS

A. Results - First module: Intensity Mapping

Figure 5 shows the average intensity maps, created by averaging the individual intensity maps of sixteen participants for a given PUC design. The contour lines indicate areas of equal perceived intensity. The maps suggest an increase in the perceived vibrotactile intensity from the bottom-left corner [4 kPa, 20 Hz] to the top-right corner [30 kPa, 100 Hz].

1) Effect of Pressure and Frequency: Fig. 6a and Fig. 6b show the effects of pressure and frequency of perceived intensity for the 0.9 mm and 1.2 mm PUC actuators, respectively. These values were measured at nine sampled locations across the parameter space as described in the Fig. 3. The perceived intensity magnitudes are reported relative to the reference stimulus [17 kPa, 60 Hz]. A negative magnitude indicates that the stimulus was perceived as being less intense than the reference, while a positive magnitude indicates that it was perceived as being more intense.

In the case of 0.9 mm PUC design, the Shapiro-Wilk normality test (with p-values adjusted by the Holm method) revealed that all groups met the normality condition. The 3 × 3 repeated-measured ANOVA results indicate a significant main effect of pressure, $\mathrm{F}(1.24, 18.64) = 197.52$, $p < .001$, $\eta_p^2 = .77$; a significant main effect of frequency, $\mathrm{F}(2, 30) = 120.82$, $p < .001$, $\eta_p^2 = .65$; and a significant interaction between pressure and frequency, $\mathrm{F}(2.13, 31.99) = 7.13$, $p = .002$, $\eta_p^2 = .06$.

In the case of 1.2 mm PUC design, the Shapiro-Wilk normality test (with p-values adjusted by the Holm method) revealed that all groups met the normality condition. The 3 × 3 repeated-measured ANOVA results also indicate a significant main effect of pressure, $\mathrm{F}(1.30, 19.46) = 147.97$, $p < .001$, $\eta_p^2 = .71$; a significant main effect of frequency, $\mathrm{F}(1.11, 16.71) = 65.69$, $p < .001$, $\eta_p^2 = .65$; and a significant interaction between pressure and frequency, $\mathrm{F}(1.73, 25.88) = 5.90$, $p = .01$, $\eta_p^2 = .03$.

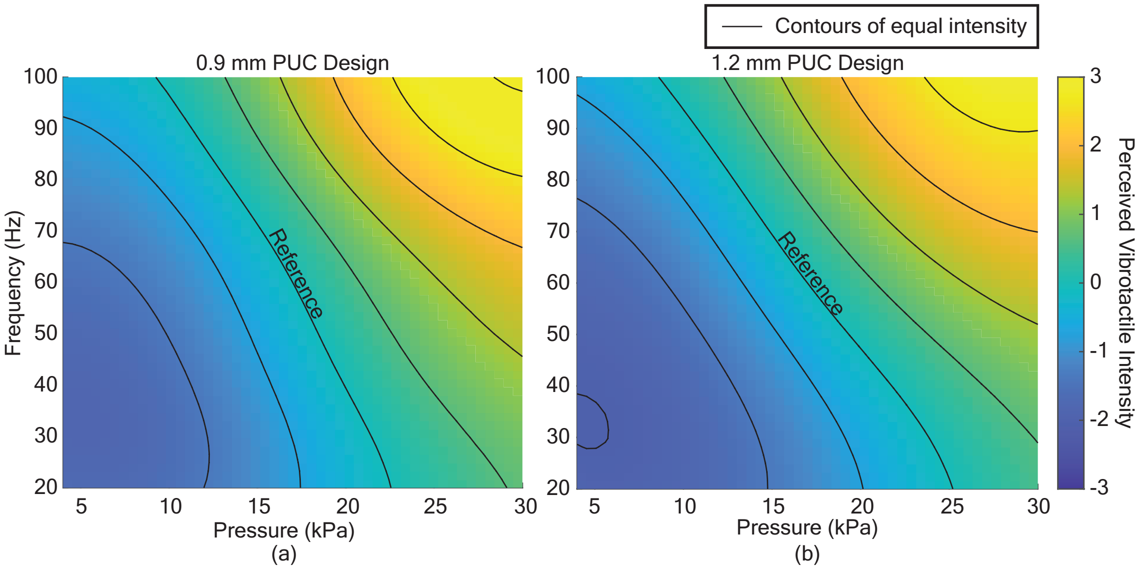
These results reinforce the trends represented in the Fig. 6a and Fig. 6b, that increasing either pressure or frequency increased the perceptual intensity of the vibrotactile stimulus. Additionally, the analysis revealed an interaction effect, indicating that the increase in perceived intensity does not follow a simple linear pattern. These observations are consistent across both the 0.9 mm PUC design and the 1.2 mm PUC intensity maps.

2) Interaction between pressure and frequency: Fig.7a and Fig.7c show the number of JNDs obtained from the 0.9 mm PUC intensity map and 1.2 mm PUC intensity map. For pressure slices, increasing frequency seems to lead to a higher number of JNDs. Similarly, for frequency slices, the figures suggest that increasing pressure results in a higher number of JNDs. Our statistical analyses confirm this notion.

Prior to the analysis, Shapiro-Wilk normality test (with p-values adjusted by the Holm method) was conducted across frequency and pressure slices of 0.9 mm and 1.2 mm PUC design data. The results show that all groups met the normality requirement.

The results of the one-way repeated-measured ANOVA for frequency slices of both the 0.9 mm PUC actuator and 1.2 mm PUC actuator on the number of JNDs indicate a significant main effect of pressure, $\mathrm{F}(1.31, 19.58) = 11.92$, $\mathrm{p} = .001$, $\eta_p^2 = .20$ for 0.9 mm PUC actuator and $\mathrm{F}(1.24, 18.65) = 6.68$, $\mathrm{p} = .014$, $\eta_p^2 = .06$ for 1.2 mm PUC actuator.

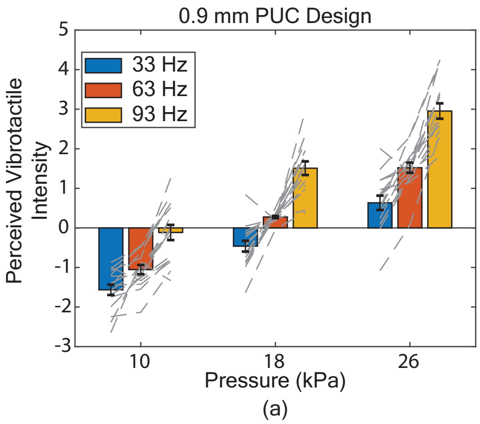
The results of the one-way repeated-measured ANOVA for pressure slices of both the 0.9 mm PUC actuator and 1.2 mm PUC actuator on the number of JNDs indicate a significant main effect of frequency on the number of JNDs, $\mathrm{F}(2, 30) = 8.14$, $\mathrm{p} = .001$, $\eta_p^2 = .16$ for 0.9 mm PUC actuator and $\mathrm{F}(1.28, 19.25) = 5.92$, $\mathrm{p} = .019$, $\eta_p^2 = .10$ for 1.2 mm PUC actuator.



(a)

(b)

Fig. 5. For the intensity mapping module, the average intensity map were created by averaging the intensity maps of all sixteen participants for a given design. The black lines represent contours of equal intensity, with the reference line corresponding to the contour of line passing through the reference stimulus [17 kPa, 60 Hz]. The spacing between lines represent one Just Noticeable Difference (JND). (a) Average perceived intensity map for the 0.9 mm PUC actuator. (b) Average perceived intensity map for the 1.2 mm PUC actuator.



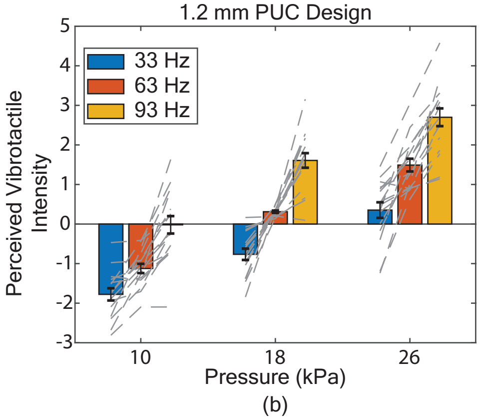
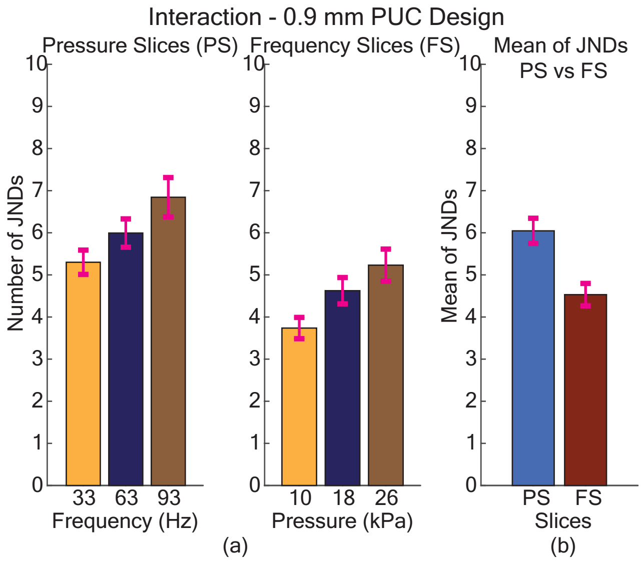


Fig. 6. Results of the intensity mapping module showing the effects of pressure and frequency on the perceived intensity. The Height of the bars represent the mean vibrotactile intensity, relative to the reference stimulus [17 kPa, 60 Hz] for each design, averaged across participants and measured at nine evenly distributed locations. As shown in Fig. 3, error bars indicate ± the standard error across these locations. Thin dashed lines indicate the individual participant data. Results show that perceived intensity increases with both pressure and frequency. (a) 0.9 mm PUC design. (b) 1.2 mm PUC design. Both designs follow the same trend.

Fig. 7b and Fig. 7d illustrate the mean of JNDs measured across three pressure slices (sky blue bars) and three frequency slices (red bars) for the 0.9 mm and 1.2 mm PUC actuators, respectively. For both PUC designs, the pressure slices resulted in a higher number of JNDs than the frequency slices, as confirmed through a paired t-test for 0.9 mm PUC design and Wilcoxon signed rank exact test for 1.2 mm PUC design. The choice of tests was based on normality checks: the 0.9 mm PUC data satisfied the normality assumption, whereas the 1.2 mm PUC data did not. For the 0.9 mm PUC actuator, the results showed a significant difference between the number of JNDs present in pressure slices (M = 5.05; SE = 0.30) and frequency slices (M = 3.53; SE = 0.27)[t(15) = 4.25, p < .001]. Similarly, for the 1.2 mm PUC actuator, a significant difference was found between pressure (M = 4.94; SE = 0.34) and frequency slices (M = 3.86; SE = 0.43), $V = 23$, p = .01825.



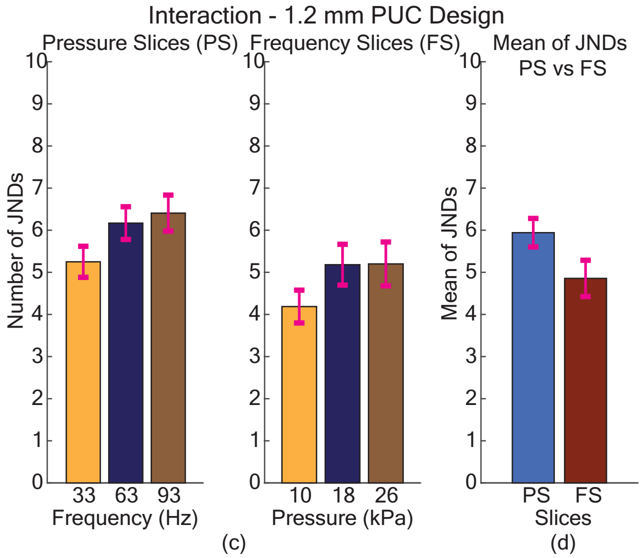


Fig. 7. Results of the interaction between pressure and frequency on perceived vibrotactile intensity for a given design, expressed as the number of Just Noticeable Differences (JNDs) relative to the reference stimulus at [17 kPa, 60 Hz]. A detailed description of how JNDs were measured is provided in Section II-G. (a) & (c) Means and standard errors of JNDs at pressure (33 Hz, 63 Hz, 93 Hz) and frequency (10 kPa, 18 kPa, 26 kPa) slices for the 0.9 mm and 1.2 mm PUC designs, respectively. Bar plots on the left show the effect of frequency on JNDs across pressure slices, and on the right, the effect of pressure on JNDs across frequency slices. (b) & (d) Means of JNDs (pressure slices in sky-blue, frequency slices in red) for the 0.9 mm and 1.2 mm PUC designs. Bar plots show that pressure slices result in higher mean JNDs than frequency slices do.

B. *Results - Second module: Level Set Estimate*

The results of the level set estimate module show that the perceived vibrotactile intensity of the reference stimulus [17 kPa, 60 Hz] on a 0.9 mm PUC actuator can be matched on a 1.2 mm PUC actuator with a lower pressure and frequency. Specifically, [17 kPa, 49.57 Hz] on the 1.2 mm actuator produces a similar perceived intensity as the reference stimulus on the 0.9 mm actuator. Likewise, [14.79 kPa, 60 Hz] on

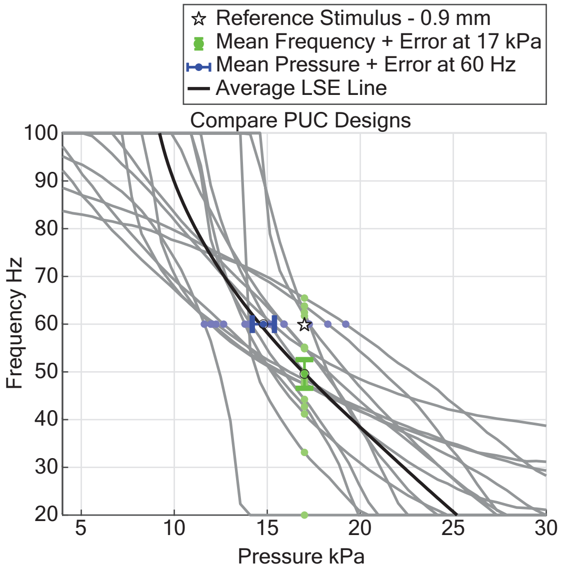


Fig. 8. Results of level set estimate module. The blue horizontal bar represents the average frequency change (at 60 Hz) in pressure on a 1.2 mm PUC actuator required to match the perceived vibrotactile intensity of a reference stimulus presented on a 0.9 mm PUC actuator. The green vertical bar represents the average frequency change at 17 kPa pressure on a 1.2 mm PUC actuator needed to match the perceived vibrotactile intensity of the reference stimulus on the 0.9 mm PUC actuator. Error bars indicate ± one standard error. Gray lines indicate individual participants' LSE lines, while the black line represents the average LSE line, derived from the mean of all participants' LSE maps. Note that the direction of the shift of the LSE line is to the left of the reference stimulus (star).

the 1.2 mm actuator also matches the reference stimulus [17 kPa, 60 Hz] on the 0.9 mm actuator (Fig. 8).

To statistically evaluate the influence of the stiffness of the PUC actuator on perceptual vibrotactile intensity, two single-sample t-tests were conducted. Normality checks confirmed that the LSE data for both pressure and frequency shifts satisfied the normality assumption, justifying the use of t-tests. In the first test, the pressure of the stimuli was set to 17 kPa, and the output metric reflected the required frequency shift for the 1.2 mm stimulus to be perceived as equally intense as the of 0.9 mm reference stimulus. In the second test, frequency was set to 60 Hz, and the required pressure shift is calculated to match the 0.9 mm reference stimulus (Fig. 8).

The magnitude of the required frequency shift ($M = 10.43, SD = 3.00$) for a 17 kPa stimulus set was significantly different from zero (t(15) $=$ 3.48, p $<$ .0034). Similarly, the magnitude of the required pressure shift ($M = 2.21, SD = 0.60$) for a 60 Hz stimulus set was significantly different zero (t(15) $=$ 3.71, p $<$ .0021).

IV. DISCUSSION

This study evaluated the perceived vibrotactile intensity delivered by soft Pneumatic Unit Cell (PUC) actuators. It examined how stimulus parameters such as pressure, frequency, and actuator stiffness-specifically varied through top layer thickness—affect this perception. In the first module, we mapped the influence of pressure and frequency on the perceived vibrotactile intensity. For visualization purpose, the average perceived vibrotactile intensity maps of the 0.9 mm PUC design and 1.2 mm PUC design, shown in Fig. 5, alludes how pressure and frequency influence intensity. In these maps, the contour lines, similar to the equal sensation lines presented by [8], provide the pressure-frequency combinations that produce equal perceived intensities for a given PUC design.

The results, based on the posterior means representing perceived vibrotactile intensity, revealed a significant effect of both pressure and frequency. This pattern is consistent across all nine sampled locations within the parameter space and holds for both PUC actuator designs. These findings align with existing studies on rigid electromechanical actuators [7], [8], which demonstrated that increasing the amplitude of a vibrotactile stimulus at a given frequency leads to a higher perceived intensity. Since the amplitude of a PUC actuator's stimulus is directly proportional to the applied pressure [13], the observed patterns in the posterior means indicate that the results from electromechanical actuators align with the findings on soft PUC actuators, as demonstrated in this study. Additionally, the analysis of posterior means revealed a significant interaction effect between pressure and frequency.

Our more in-depth analysis on the interaction effect based on JNDs indicated that a change in both pressure and frequency simultaneously contributes to a greater change in perceived intensity than when either of parameter is varied independently, and that this holds for the pressure-frequency slices considered in the study. This finding is consistent with the work of [5], which demonstrated with rigid vibrotactile actuators that modulation of both frequency and amplitude leads to a more rapid increase in perceptual intensity compared to modulating either frequency or amplitude alone. Alongside demonstrating the interaction effect, the number of JNDs highlighted the ability of PUC actuators to generate a diverse range of perceptually distinct stimuli, demonstrating their versatility across the considered pressure and frequency range.

In addition to pressure and frequency, the study also explores how actuator stiffness influences perceived intensity, as actuator design could affect actuator behavior. We compared two actuator designs with different top layer thicknesses. Specifically, the 0.9 mm PUC actuator, with a top layer thickness of 0.9 mm, is less stiff than the 1.2 mm PUC actuator, which has a 1.2 mm thick top layer. As reported by [13], this difference in stiffness leads to reduced vibration amplitude in the 1.2 mm PUC actuator compared to the 0.9 mm design. The results of this study indicate that actuator stiffness significantly affects perceived vibrotactile intensity. The 1.2 mm PUC actuator matched the reference intensity of the 0.9 mm actuator at significantly lower pressure and frequency. This finding contrasts with our initial hypothesis, which assumed that a stiffer actuator would produce lower amplitude for a given pressure. Based on this assumption, we expected a positive pressure shift (greater than 17 kPa) rather than a negative shift (less than 17 kPa). This discrepancy suggests that actuator amplitude is not the only factor influenced by actuator design.

Although a definitive explanation is not yet established, we hypothesize that the interaction between two soft bodies, the PUC actuator and the human fingertip, is complex and may lead to variations in effective contact area during stimulus presentation. Although both actuators have the same top surface area, the difference in the amplitude of vibration between both actuators [13] could result in different dynamic contact behaviors, potentially influencing the perceived intensity.

Forta et al. [9] investigated the role of contact area in vibrotactile perception and found that larger contact areas reduce detection thresholds due to spatial summation. At suprathreshold levels, their study showed that at 10 Hz, a larger contact area led to lower JNDs, whereas at 125 Hz, a smaller contact area was more discriminable. These findings suggest that contact area can modulate both detectability and discriminability depending on frequency and receptor channel involvement.

In our study, if the stiffer actuator maintained a more stable or broader contact area during vibration, it may have enhanced spatial summation, thereby increasing perceived intensity. However, this remains speculative. A dedicated study analyzing the dynamic contact behavior between the actuator and skin would be necessary to evaluate how stiffness influences effective contact area and, consequently, perceptual intensity.

The current study employed a Non-Parametric Bayesian approach, implemented through the AEPsych toolbox, for psychophysical exploration. This method efficiently estimates the latent function F, which quantifies subjective perception of vibrotactile intensity, while requiring significantly fewer trials compared to traditional psychophysical techniques. For example, the subjective scaling method used by [8], which has a similar experimental aim, involved 600 trials per participant across 10 frequencies and 10 intensity levels, excluding threshold estimation at each frequency. Similarly, the matching-by-adjustment procedure, also reported by [8], which used 2 reference frequencies, 11 intensity levels, and 10 test frequencies, required approximately 1,300 trials per participant. In contrast, the Non-Parametric Bayesian approach in our study required only 280 trials per participant, resulting in the evaluation of a detailed perceived intensity map across various pressure levels, frequencies, and actuator designs.

Nonetheless, there are certain fitting limitations inherent to the Non-Parametric Bayesian approach. Specifically, this approach assumes that the subjective metric—such as perceived vibrotactile intensity—is continuous within the tested parameter range. As a result, the selection of pressure and frequency ranges was constrained by this assumption. The perceptual continuity constraint of the method is defined as the requirement that a set of stimuli can be described using similar perceptual terminology and engage the same mechanoreceptors for interpretation. In the context of vibrotactile stimuli, extensive literature has reported the engagement of different mechanoreceptors based on the stimulus frequency [2]. Based on the review by [2] and observations from our pilot study, a frequency range of 20 Hz to 100 Hz was selected to meet this criterion. Regarding the pressure parameter, the range of 4 kPa to 30 kPa was chosen mainly due to the hardware limitations. Specifically, delivering consistent pressure below 4 kPa poses challenges due to hardware limitations, while pressures exceeding 30 kPa result in excessive bellowing in PUC actuators [[13]]. Under these constraints, the perceptual intensity maps generated in the study using the AEPsych toolbox quantify vibrotactile stimulus intensity as posterior means, with the reference stimulus assigned a value of zero.

Overall, the study underscores how parameters such as pressure, frequency and actuator stiffness shape the perceived vibrotactile intensity when delivered using a soft pneumatic actuator. These insights pave the way for understanding the perception of vibrotactile stimuli delivered using soft actuators for haptic applications, particularly in tailoring tactile feedback for diverse use cases such as for teleoperation tasks [5] or for hand held devices [3], [29].

V. CONCLUSION

This study characterized the perceived vibrotactile intensity delivered by Pneumatic Unit Cell (PUC) actuators by examining the roles of pressure, frequency, and actuator stiffness across specific parameter ranges. Our findings show a significant influence of these factors on the perception of vibrotactile stimuli.

The results demonstrated a positive effect of pressure and frequency on the perceived intensity. Analysis based on the number of Just Noticeable Differences (JNDs) revealed that both parameters enhance the perceptual vibrotactile intensity, with higher pressure and frequency levels yielding more perceptually distinct stimuli. The study also revealed that the frequency exhibited a stronger influence on the number of JNDs compared to pressure, highlighting the nature of the influence of both parameters in rendering vibrotactile feedback using soft PUC actuators.

Finally, a comparison of two PUC actuator designs with different stiffness revealed that the actuator with a stiffer design (1.2 mm) achieved equivalent perceived intensity at lower pressures and frequencies compared to the actuator with a less stiff design (0.9 mm). This shows that, among soft actuators, the stiffness of the actuator can significantly influence the perceptual intensity of the vibrotactile stimulus.

In summary, this study provides key insights into the combined influence of stimulus parameters—pressure and frequency—and actuator design on the perception of vibrotactile intensity. These findings lay a robust foundation for advancing the design of soft actuators and establishing more precise guidelines for an intuitive rendering of vibrotactile feedback in haptic technologies.

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VI. BIOGRAPHY SECTION

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