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Article

Evaluating the Optimum Distance between Voice Coil Actuators Using the Relative Point Localization Method on the Forearm

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Abstract: While vibrotactile stimulation shows promise for sensory substitution devices, a crucial question concerns vibrotactile spatial resolution. We examined the optimum distance between three voice coil actuators (model: lofeltL5) on the forearm. Three actuators were embedded in a fabric-based vibrotactile sleeve where the actuators were placed in enclosures 3D-printed on the fabric. We used the relative point localization method where observers must discriminate whether two successive stimulations are in the same location or not. The resolution was measured for five vibrotactile sleeves, each with different distances between the actuators on the longitudinal axis of the forearm. The various distances were tested in a random order. In experiment one, pairs of stimuli were delivered sequentially in a random order to two adjacent actuators of the tactile sleeve on the upper side of the forearm. The task was to identify the perceived direction of the second stimulation (up, down, or the same) relative to the first one. Experiment two involved the same procedure but for the underside of the forearm. Taking the restrictions of the physical dimensions of the forearm and the design considerations into account, our results suggest that 20 mm is the optimum distance between the voice coil actuators (Model: Lofelt L5) for successful discrimination with high accuracy between the two stimulus locations on the forearm. There were no significant differences between the upper and undersides of the forearm.

Keywords: vibrotactile; voice coil actuator; wearable device; tactile stimulation; vibratory stimulus; spatial acuity; stimuli localization

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Citation: Yeganeh, N.; Makarov, I.; Stefánsson Thors, S.S.; Kristjánsson, Á.; Unnthorsson, R. Evaluating the Optimum Distance between Voice Coil Actuators Using the Relative Point Localization Method on the Forearm. *Actuators* **2023**, *12*, 6. https://doi.org/10.3390/act12010006

Academic Editor: Richard Yongqing Fu

Received: 19 November 2022
Revised: 18 December 2022
Accepted: 19 December 2022
Published: 22 December 2022

1. Introduction

Vibrotactile stimulation shows promise for sensory substitution in assistive devices for people with visual or auditory impairment [1,2]. Vibrotactile devices can be used to compensate for lost information by providing vibratory stimulus signals that can convey information that cannot otherwise be used because of perceptual deficiencies. Understanding the most feasible number and locations of tactile stimulation is one of the critical questions that must be answered before vibrotactile sensory substitution displays can be implemented. The interspacing between the actuators will have a decisive effect on the perception of the vibrotactile stimulation and on whether the signals can be spatially differentiated from each other. The minimum distance between two objects that can be discriminated has been investigated since the 19th century using various techniques [3–5]. Weber introduced a psychophysical two-point threshold (2PT) method for assessing the minimum distance between two simultaneously stimulated points where the two stimuli can be spatially discriminated [5]. Many studies of tactile spatial acuity have used this 2PT method, where the purpose has been to determine the detection threshold between two stimulus locations—whether the two stimulations are perceived at the same or different locations [6–14]. Some studies have indicated that results on the 2PT task can be contaminated by non-spatial cues that may result in inflated estimates of spatial acuity. For instance, two points might feel further apart than they actually are. These cues can also be temporal. If the two points stimulations are not applied simultaneously, the participant may perceive two contacts even if they are unable to spatially discriminate the points. Magnitude cues, where interactions between stimuli are not expected at the single-neuron level, can also affect performance. The two-point orientation threshold (2POT), where participants must discriminate the orientation (horizontal vs. vertical) of two points of contact, may be a better measure of spatial acuity, since it avoids the non-spatial cues [15–17].

It is also important to note that tactile spatial acuity differs by body part [18]. For example, the 2PT is much larger on the forearm than on the fingertips [4,19,20]. Reports of 2PT results should always be accompanied by a detailed description of how the test was conducted [16,21,22], because different protocols and tools have been used [23]. Notably, other findings show that training may influence 2PT measurements [24,25]. Moreover, other methods, such as tracking of absolute point localization (PL), have revealed a lower value than the 2PT [4,6]. Despite these controversies, 2PT remains a valuable resource [4].

Even though acuity for tactile point stimulation has been investigated extensively, less is known about vibrotactile spatial acuity. Our research group has studied vibrotactile devices over the last few years [26–29]. The aim has been to gain knowledge about the qualities of vibrotactile perception for potential use in sensory substitution devices [29]. We have, for example, investigated the relative vibrotactile spatial acuity in the back region of the human body using coin cell motors, finding the minimum threshold by decreasing the center-to-center inter tactor distance. The measured minimum threshold was 13 mm from center to center (c/c). Note that this threshold only applies to the central area of the back and cannot easily be generalized to other body parts [26].

Another way of measuring the spatial accuracy of the interspacing between localized stimuli in tactile displays is by applying the point localization (PL) method. The method has been widely used to analyze spatial acuity for different interspacings between stimulators. This method has been used to measure absolute spatial acuity [30], where the vibrotactile stimulus was presented at fixed distances. The task was to identify the location of the vibrating actuator in the array. Lindeman and Yanagida [31] tested absolute localization accuracy using prototypes with different numbers of tactors embedded on the subjects' backs. The highest accuracy was found for inter-tactor spacings of 60 mm, with 84% accuracy on the discrimination task. Cholewiak [30] investigated spatial accuracy using the PL method, presenting the stimuli on the abdomen. Performance was a function of separation among loci and, most significantly, of the location on the trunk.

Because of potential problems with the 2PT and PL methods as discussed above, some researchers have instead recommended the use of the relative point localization method (rPL) [32–34], where observers must discriminate whether two successive stimulations are in the same location or not, and this is the method that we chose for our measurements.

2. Materials and Methods

2.1. The Current Goals

Our aim was to evaluate the optimum interspacing between Lofelt L5 voice coil actuators on the forearm. Our aim was to find the minimum distance where two vibrotactile stimulations can be discriminated with high accuracy. The goal was to use the results to optimize the structure of a vibrotactile sleeve in sensory substitution devices. We used the relative point localization method (rPL) on both sides of the forearm, measuring the relative spatial acuity for vibrotactile stimulation. The aim was to formulate guidelines for minimum intervals for successful separation of different loci of stimulation from the voice coil actuators (Lofelt L5) on the forearm. The relative point localization task measured observers' ability to determine the direction of a second stimulus relative to the initially presented one on each trial. The forearm has limited space to place multiple actuators next to each other laterally, and we therefore tested different distances in the longitudinal direction. The feasible upper limit is therefore set by how far apart the actuators can be placed, considering that the forearms of potential users will differ in length.

Our results indicate that a distance of 20 mm is the best distance between actuators on both sides of the forearm, when the spatial limits on design are considered. The results of this study will be helpful for the continued development of our current design of the vibrotactile sleeve and provide valuable insights for the creation of forearm-mounted vibrotactile displays using voice coil actuators (Model: Lofelt L5) by providing information regarding the optimum distance between actuators along the forearm.

2.2. Equipment and Setup

2.2.1. Actuators

Voice coil actuators (model: Lofelt L5) were employed to generate vibratory stimulation (Figure 1A,B). The L5 actuator is an extended-band actuator that allows independent manipulation of the frequency and amplitude utilized in implementing haptic stimulation for many scientific purposes. Their high acceleration, light weight, high efficiency, and inexpensiveness, along with other advantages, make voice coil actuators ideal for various vibrotactile displays. The Lofelt L5 voice coil actuator provides parallel vibrations on the skin [35]. In this study, the actuators were embedded in housings that were 3D-printed on a power mesh fabric material. Tables 1 and 2 show the physical, haptic, and electrical characteristics of the Lofelt L5 [35].

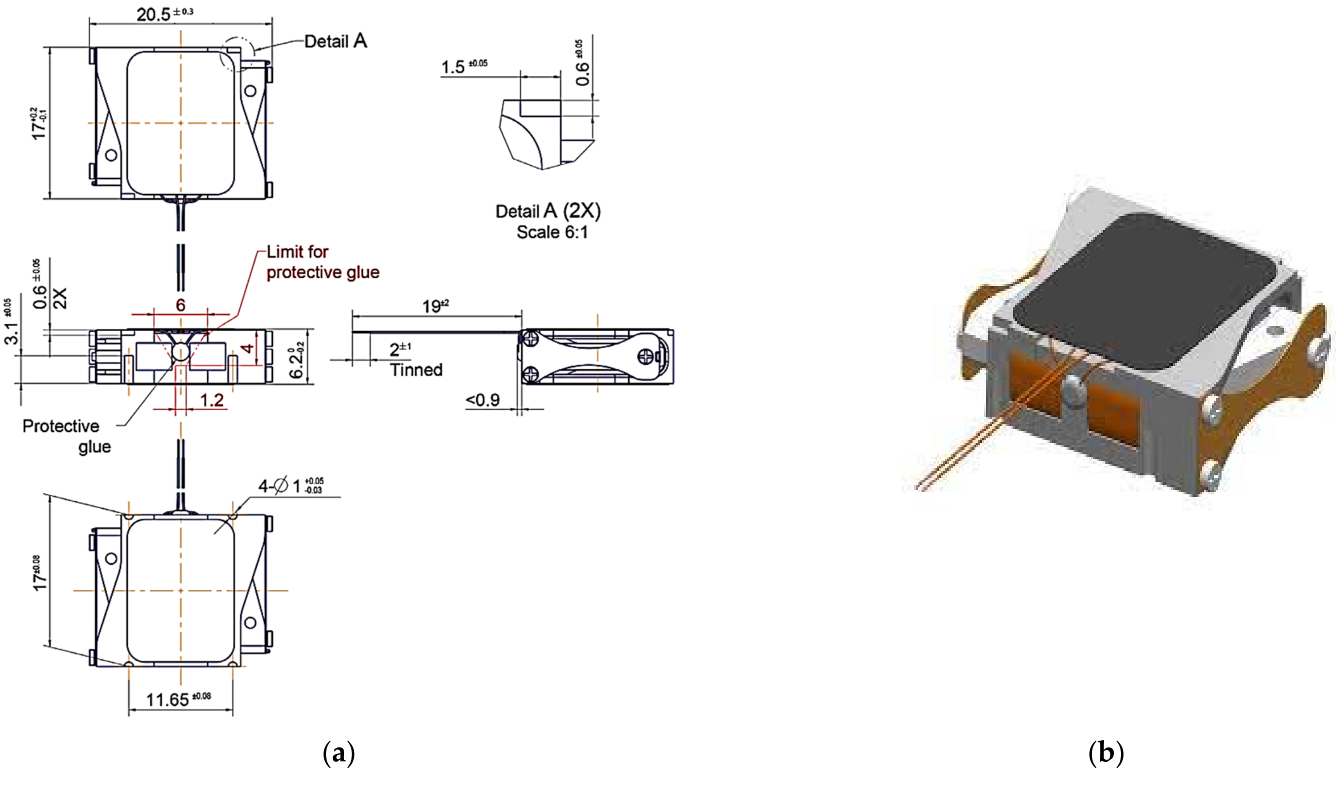


Figure 1. (**a**) Technical and dimensional information for the L5 voice coil actuator, and (**b**) the voice coil actuator (Model: Lofelt L5) used in this study [35].

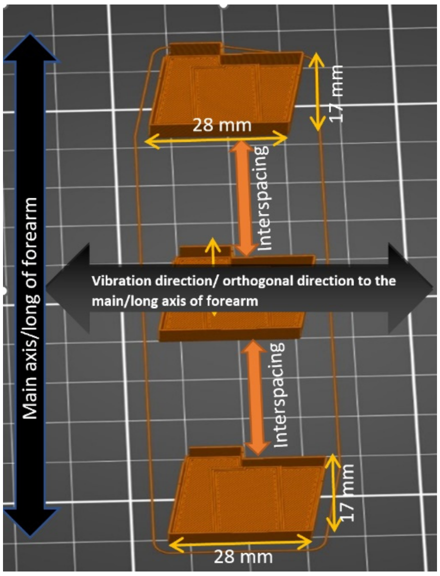
Table 1. Physical Characteristics of Lofelt L5 [35].

Dimensions (W × D × H)	At rest: 17.0 × 20.5 × 6.2 mm Max displacement: 17.0 × 25.5 × 6.2 mm
Weight	6 g +/− 0.5 g

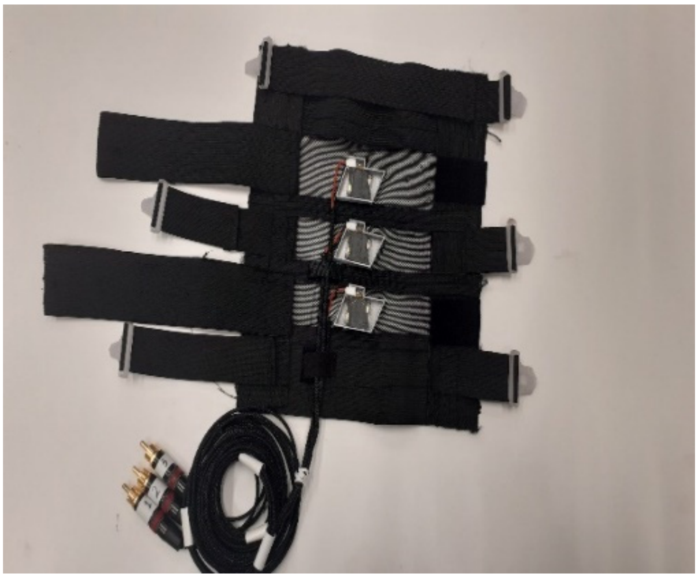
Table 2. Haptic, Electrical, and Acoustic Characteristics of Lofelt L5 [35].

Maximal Voltage	1.4 Vrms at f0
Resonance Frequency (f0)	65 Hz ± 5%
Frequency Range	Min. 0.5 G over 35 Hz–1 kHz
Nominal Impedance	8 Ω at f0
Power Handling	Maximum: 320 mW
Current Consumption	Average at medium volume: 10 mA, bass music use-case Average at maximum volume: 57 mA, bass music use-case

Several different versions were tested for the enclosure design. The final design involved 3D-printing the enclosure for the actuator straight onto the fabric material (Figure 2B). The enclosures allow the actuator to vibrate freely. The physical dimensions of L5 actuators are W: 17.0 × D: 20.5 × H: 6.2 mm, and when vibrating at maximum displacement, they are W: 17.0 × D: 25.5 × H: 6.2 mm (Table 1). The dimensions of the enclosures are W: 17.0 × D: 28 × H: 6.2 mm (Figure 2A,B).



(**a**)



(**b**)

Figure 2. (**a**) Overview of designing the Lofelt L5 actuators along the forearm; and (**b**) an example of a wearable vibrotactile sleeve and the configuration of the actuators.

A Prusa Slicer and a Prusa MK3s 3D printer were used to print the actuator housing. The fabric works as a scaffold to hold the actuators in place on a flexible and elastic surface. The actuators are firmly fastened inside the enclosures. There are no fabric layers between the actuators and skin on the stimulation surface (point of contact). In addition, the thin, flat surface of the plastic case is connected to the skin directly and transmits the vibration signals to the skin. Accordingly, the vibration is transmitted to the user's forearm through the thin (the thickness is approximately 2mm) surface of enclosures against the skin resulting in a back-and-forth vibration parallel to the skin's surface. Enclosures prevent the moving permanent magnet inside the L5 casing from scratching against the participants' skin or causing damage to the elastic material.

2.2.2. Tactile Sleeve and Hardware

Five soft and thin fabric-based vibrotactile sleeves were used in this experiment. A Power Mesh fabric was used (Power Mesh fabric material: 90% nylon and 10% spandex), which made the wearable sleeve comfortable and user-friendly. Stretch straps with Velcro were used to secure the haptic sleeve onto the forearm and to make it easy to adjust according to the thickness of the user's forearm. The wearable tactile sleeves each consisted of three voice coil actuators (Lofelt L5) that were placed in housings that were 3D-printed onto the fabric. The actuators were laid along the forearm in 3 × 1 array (longitudinal orientation) that caused tangential vibration and lateral skin stretch. In this study, five vibrotactile sleeves with different inter-actuator spacings of 20 mm, 15 mm and 10 mm, 5 mm and as close as physically possible (no space between actuators, in other words 17 mm center-to-center) were used to evaluate the optimum inter-actuator distance that would make two stimuli differentiable with high accuracy (Figure 2A,B and Figure 3). For design reasons, the upper limit tested was the 20 mm separation between the actuators.

Figure 3. The five vibrotactile sleeves with different interspacings between actuators that were used in the experiment.

The prototype was connected to audio hardware via wired interfaces. The audio hardware had four main components: a digital audio interface (RME MADIface XT: IMM Elektronik GmbH, Mittweida, Germany) [36], digital-to-analog converters (Ferrofish A32), multichannel amplifiers, and voice coil actuators (Lofelt L5). The MADIface XT receives information from a computer via a USB cable and sends the signal to the Ferrofish A32 Analog-to-Digital/Digital-to-Analog (AD/DA) converter. Ferrofish A32 then conveys the signal to the amplifier, which then sends the amplified signal to the actuators [36].

2.3. Procedure

The sites assessed in the localization experiments were the upper and undersides of the forearm. The upper forearm has mostly hairy skin, with a set of mechanoreceptors that differs from those on the glabrous skin of the underside of the forearm [37]. Five different tactile sleeves were tested (five different spacings between the actuators), with three voice coil actuators placed on the longitudinal line on the forearm (causing tangential vibration and lateral skin stretch), while the hand rested on pad support. Before the main experiment, the procedure and tactile stimulation protocol were fully explained to the participants, and their written informed consent was obtained. Before the main experiment began, they completed a few training trials to familiarize themselves with the setup, apparatus, and the vibratory stimulus. The experiments were performed in an anechoic chamber. Two experiments were performed; one where the upper side of the forearm was stimulated (experiment one, see Figure 4A) and one where the underside of the forearm was stimulated (experiment two, see Figure 4B). The experiments were designed to determine the minimum interspacing between actuators that we could use so that the different sites of stimulation could easily be told apart.

(a)

(b)

Figure 4. A participant wearing a vibrotactile sleeve with his hand on the cushion, using the headphone to block out external auditory cues and responding to the vibrotactile feedback by pressing the correct key on the wireless keyboard. There were two experiments: (**a**) on the upper side of the forearm in experiment one; (**b**) and on the underside of the forearm in experiment two.

The duration of the two experiments was approximately 40 min for each participant. Each experiment consisted of five steps of five tactile sleeves (with different inter-spacing between actuators) presented in a different random order for each participant. Twenty-four trials were conducted for each tactile sleeve. Each test consisted of the sequential activation of two adjacent actuators with an interstimulus interval of 50 ms. This time duration was chosen in light of the optimal delay range between sequential pulses (between 20–250 ms) to minimize potential mislocalization [38]. The selected actuators were turned on for 200 ms, and the intertrial time for the sequential trials was 500 ms. The frequency and amplitude of all the stimuli were the same during all trials (100 Hz and 0.125 of Min 0.5G acceleration, respectively) to ensure that the vibration acceleration was equal during all experiments due to the nonlinear frequency responses of our used actuators. This ensured that all signals resulted in the same vibration intensity on the skin during the test.

The participants were totally unaware of the particular vibrotactile patterns in a given trial and the sleeve differences to avoid any biases.

2.3.1. Participants

Eight healthy individuals (aged 21–38 years, with a mean of 29 years) participated in this study. They confirmed that they had no significant issues with exposure to hand-transmitted vibrations. Each participant signed a written informed consent form.

2.3.2. Experiment One

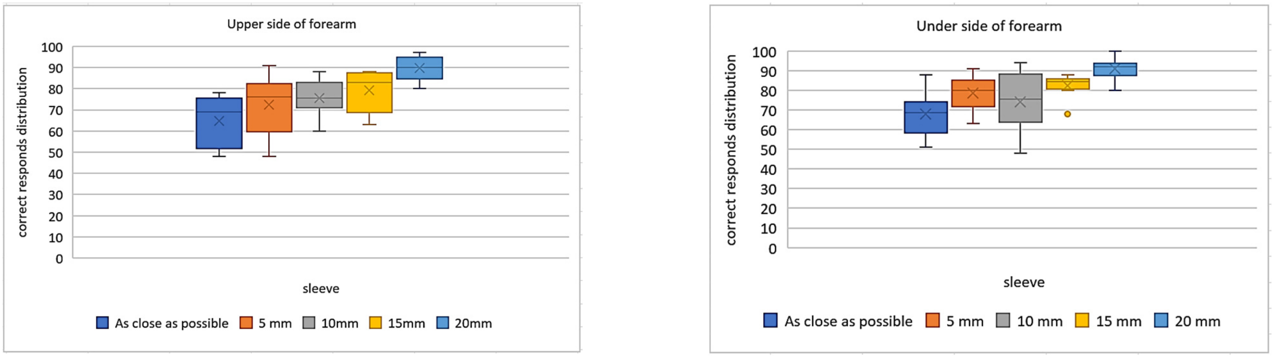
The participants sat on a chair in the anechoic chamber, with their left hand resting on the table on the padded support. During the experiments, the participants donned noise-cancellation headphones that played white noise to mask environmental and mechanical noises. The tactile sleeve was attached firmly to the forearm by thin double-sided adhesive Velcro. Five different vibrotactile sleeves were used, differing in the interspacing between their actuators. Twenty-four pairs of vibrotactile stimuli were conveyed through the voice coil actuators for each tactile sleeve. Each trial consisted of a pair of stimuli sequentially delivered to the forearm. The task was to indicate the perceived direction of the second stimulus relative to the initial stimulus' locus on each trial. In all the tests, the participants registered their responses by pressing one of the three buttons on a wireless keyboard they held with their hand, indicating whether the second response was closer to the fingers, closer to the elbow, or in the same location, relative to the first stimulation (Figure 4A).

2.3.3. Experiment Two

Experiment two involved the exact same procedure as experiment one, but this time, the stimulation was presented on the underside of the forearm. The same five vibrotactile sleeves used in experiment one were also used in experiment two, with the actuators placed equidistant in a line along the length of the underside forearm. This time, observers had their palm facing upwards (Figure 4B).

3. Results

Figure 5 shows the median correct responses for five different tactile sleeves for the observers, along with measures of dispersion. The box plot shows that the highest median accuracy was found for the tactile sleeve with a 20 mm inter-distance between enclosures on the upper side (90%, see Figure 5A) and underside of the forearm (92%, see Figure 5B) compared to all the other tactile sleeves used in this study, with smaller interspacings. The median accuracy was lowest for the tactile sleeve with no space between the enclosures (see Figure 5A,B) compared to other sleeves on the upper side and underside of the forearm (the median was 69% on both sides).



(**a**) (**b**)

Figure 5. Box–whisker plot comparing the accuracy (percent correct, *y*-axis) between the five different tactile sleeves with various inter distances between enclosures (*x*-axis): (**a**) the percent correct for the upper side of the forearm; and (**b**) the percent correct for the underside of the forearm. The box length represents the interquartile range (IQR), the 25% and the 75% limits, and the horizontal bar inside the box shows the median value. The ends of the box plot represent minimum and maximum values.

A two-way repeated measures ANOVA with the factors upper versus lower forearm and actuator interspacing (along with Bonferroni corrected post hoc tests) was calculated to assess the significance of the differences in accuracy for the different distances between the actuators and the differences between the accuracy for the underside and upper side of the forearm. The two-way ANOVA also enabled us to assess the interaction between these two factors, such as whether the effect of inter-distance varies between the upper side and the underside of the forearm.

The two-way repeated measures ANOVA revealed a large main effect of interspacing of the actuators upon detection accuracy (F (4,70) = 11.71; $p < 0.05$). There was no effect of the side of the forearm upon accuracy (F (1,70) = 1.21; $p = 0.27$), nor was there any significant interaction between these factors (F (4,70) = 0.29; $p = 0.88$).

This means that as the difference between the actuators increased, accuracy in the discrimination task improved significantly, reaching a very high accuracy level for the 20 mm distance (some participants had 100% accuracy). The accuracy for the under and upper sides of the forearm did not differ significantly on the other hand.

Post hoc tests (Bonferroni corrected) were performed to assess significant differences between different tactile sleeves. After the Bonferroni correction, the statistical threshold was adjusted to $p < 0.005$. The results of the post hoc test showed that on the upper forearm there were significant differences between the pair of sleeves where actuators were placed as close as physically possible ([ACAP], no space between actuators, in other words, 17 mm center to center) and the sleeve with a 20 mm interspace had [*p*-value = 0.0004] (Table 3). This was also the case for the underside of the forearm (Table 4).

Table 3. Post-hoc test *p*-values (upper forearm).

	5 mm	**10 mm**	**15 mm**	**20 mm**
ACAP	0.2552	0.0550	0.0186	0.0004 *
5 mm		0.5902	0.2809	0.0129
10 mm			0.4511	0.0107
15 mm				0.0342

* Significant at $p < 0.005$.

Table 4. Post-hoc test *p*-values (under forearm).

	5 mm	**10 mm**	**15 mm**	**20 mm**
ACAP	0.0624	0.03806	0.0096	0.0004 *
5 mm		0.4994	0.3255	0.0115
10 mm			0.1845	0.0164
15 mm				0.0139

* Significant at $p < 0.005$.

The data distribution was highest for the tactile sleeve with 20 mm between enclosures on the upper side of the forearm with a median level of 90%, and the accuracy range was from 80% to 97%. For the underside of the forearm, the median was 92%, and the accuracy ranged from 80% to 100%. The results for the 20 mm interspacing therefore reveal high response accuracy and all participants showed relatively high levels of stimuli identification on both sides of the forearm.

Although the median values for the underside of the forearm were slightly higher than for the upper ones, the ANOVA revealed no significant differences between the sides of the forearm. We therefore cannot draw strong conclusions about better stimulus recognition on the underside of the forearm compared to the upper side. Further investigations are needed for any firm conclusions on this.

The fact that accuracy is higher with increasing interspacing between actuators is interesting, but what does this mean for the design of a sensory substitution device with stimulation on the forearm? The forearm has limited space, and realistically, there are upper limits to the distance that can be used [39]. When information from our previous designs and practicalities of future designs is taken into account, we decided to have the 20 mm distance as our upper limit. Thankfully, our results indicate that the performance for the 20 mm distance on our relative PL task is very close to ceiling performance.

Our study, therefore, suggests that the tactile sleeve with a 20 mm distances between the voice coil actuators (model: Lofelt L5) can be considered the optimum design for a tactile sleeve using multiple voice coil (Lofelt L5) actuators, providing high accuracy of stimuli discrimination, considering the restrictions of the physical dimensions of the surface of the forearm as the site of the wearable vibrotactile devices.

4. Conclusions

Increased advances in vibrotactile displays highlight the necessity of psychophysical investigations into the mechanisms underlying human tactile perception. One of the main challenges in designing tactile devices is analyzing what information can be transmitted tactually and which stimulation parameters can effectively convey information. One issue involves an empirical investigation of the maximal throughput of the skin.

How many tactors can be configured, how densely can they be placed next to each other before their loci become indistinguishable, and how can high accuracy be maintained to convey the information effectively?

For designs using closely spaced tactors, vibrotactile localization accuracy on the skin is essential. Information will be lost if vibrotactile actuators are placed so close to each other that their signals cannot be distinguished. The interspacing of actuators has a crucial effect on the resolution of vibrotactile stimuli to be differentiated from each other. In addition, this evaluation is essential for designing tactile displays so that as many tactors as possible can be placed within a defined area.

Psychophysical studies on tactile spatial acuity of different body parts can provide the required empirical basis for determining the optimal stimulation type for tactile devices. Optimum interspacing between actuators can provide high-resolution distinguishable stimuli to convey tactile information effectively. There has been a considerable amount of research on the tactile sensory capabilities of the hands and fingers, but comparatively little research has been carried out on the forearm. Although forearms are generally less sensitive than the other part of the hand (for instance, the fingers [40]), we need to use more stimuli spread over a larger surface area to compensate for this decreased sensitivity. Nevertheless, determining the optimum loci of actuators on the forearm is crucial.

This study provides guidelines for forearm-mounted wearables using the Lofelt L5 voice coil actuator in terms of comparing the accuracy rate on the upper side and underside of the forearm and determining the optimum interspacing of actuators to keep the stimuli distinguishable with high accuracy.

This paper systematically investigated the relative spatial acuity of the forearm using vibrotactile sleeves. Our objective was to determine the optimum distance where two vibrations of two voice coil actuators could be told apart spatially with high accuracy. Our research group has a long-term experience in investigating vibrotactile displays [1,2,26–29,41], and optimizing the configuration of actuators in our recent wearable vibrotactile sleeve was the inspiration for this study. The average forearm length based on the anthropometric parameters of the studied population is approximately 20.2 cm for females and 23.9 cm for males [39] which places constraints on our haptic designs.

Taken as a whole, the outcome of our study could be used to develop forearm mounted vibrotactile wearables using Lofelt L5 to obtain high-resolution signals and distinguishable vibrotactile information. First and foremost, we report localization rates for vibrotactile stimuli on the forearm for our purposes, using five different tactile sleeves consisting of three voice coil actuators on the upper side and underside of the forearm. We tried to determine the lowest interspacing that still allows discrimination with high accuracy. The results of the experiment indicate that 20 mm interspacing between actuators (Lofelt L5) yields very high performance with some participants at ceiling (Figure 5, that shows accuracy rates between 80% and 100% (median = 92%) on the under forearm and accuracy rates between 80% and 97% (median = 90%) for the upper forearm) and was therefore chosen as the optimal distance between the actuators. We found that placing the voice coil actuators (Lofelt L5) at a 20 mm inter-distance in the longitudinal arrangement resulted in significantly better discrimination accuracy than when there was no interspacing between the actuators on both sides of the forearm ($p < 0.05$). The results were similar for the upper and under sides of the forearm. We investigated both sides of the forearm to determine whether there was a significant difference between the accuracy of the responses and forearm sides. The evaluation and comparison of the results extracted from the current study revealed no statistically significant differences between the accuracy rate and the forearm's sides.

This information can be used to assist in formulating guidelines for inter-actuator spacing (voice coil actuator model: Lofelt L5) used in tactile displays that generate vibrotactile stimulation on the forearm (Figure 2A).

Several other authors have also designed forearm-mounted displays; Piateski and Jones designed a 3 × 3 array of tactors for the underside of the forearm. Using this device, they empirically studied the ability to recognize simple patterns, including activating lines of eccentric rotating tactors. The detection accuracy that they measured ranged between 80% and 96% [42].

The threshold found in our study is valid for the forearm site and the type of actuators (voice coil actuators model Lofelt L5) we used. The variance in findings of spatial acuity might have stemmed from different actuator types applied to different body parts and different methods of evaluation. Comparisons between findings of vibrotactile spatial acuity thresholds are difficult because of the complex nature of vibrotactile stimulations. Our results indicate that a distance of 20 mm is the best distance between actuators on both sides of the forearm, when the spatial limits on design are considered. The results of this study will be helpful for the continued development of our current design of the vibrotactile sleeve and provide valuable insights for the creation of forearm-mounted vibrotactile displays using Lofelt L5 voice coil actuators.

Author Contributions: N.Y. contributed to the methodology, formal analysis, investigation, data curation, and writing—original draft preparation. I.M. contributed to the methodology. S.S.S.T. contributed to the software. Á.K. contributed to the methodology, writing—review and editing and acted as a co-supervisor. R.U. contributed to the methodology, writing—review and editing, and supervision. All authors have read and agreed to the published version of the manuscript.

Funding: The work described in this paper was funded by Nordic Sound and Music Computing (project no. 86892) and RANNÍS Technology Development Fund (project no. 1910271).

Institutional Review Board Statement: The experiments were run in accordance with the requirements of the local ethical committee and in accordance with the Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: We give thanks to Hafliði Ásgeirsson from the ACUTE group of the university of Iceland for assistance and fabrication.

Conflicts of Interest: The authors declare no conflict of interest.

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